PhD Dissertation

APPLICATIONS AND NEW DEVELOPMENTS IN PHENOLOGICAL RESEARCH: MONITORING, MODELLING AND OUTLOOK

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2017

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List of Abbreviations

AIC Akaike's Information Criterion

AVHRR Advanced Very High Resolution Radiometer

BBCH-system Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie-system (used for coding phenological growth stages of plants)

BF Beginning of flowering. In Chapter 5 it is indicated as flowering onset (**FO**). In other Chapters, the expression may occure as first flowering date, flowering onset, flowering date (Chapter 4), flowering time, timing of flowering – dependently of the papers, as they were published.

BR Beginning of ripening

CCF Cross correlation function

COST Cooperation in Science in Technology

CS Citizen science

doy Day of the year (with 1st of January as the starting point). In Chapter 5 it is expressed as **day**, while it also occure (Chapter 4) as **time in days**.

EUMETNET the network of European Meteorological Services

EVI Enhanced Vegetation Index

FL appearance of First leaves

FO see BF

GDD Growing degree days

HMS Hungarian Meteorological Service

IPCC Intergovernmental Panel on Climate Change

LF Leaf falling

LR test Likelihood ratio test

MAE Mean absolute error

MAPE Mean absolute percentage error

MODIS Moderate Resolution Imaging Spectroradiometer

NAO North Atlantic Oscillation

NMHS National Meteorological and Hydrometeorological Service

NDVI Normalized Difference Vegetation Index

NS-Pheno North–South Phenological

PEP725 Pan European Phenology 725 Project

RMSE Root mean square error

SD Standard deviation

Sp Species

$\mathbf{T}_{\mathrm{eff}}$ Effective temperature

USA-NPN USA National Phenology Network

ZAMG Zentralanstalt für Meteorologie und Geodynamik (Austrian national meteorological service)

CHAPTER 1

Preamble

1.1 General introduction

According to the newest Intergovernmental Panel on Climate Change (IPCC) report, most ecosystems are vulnerable to climate change even at rates of climate change projected under low- to medium-range warming scenarios (Cramer *et al.*, 2014). Furthermore, changing climate exacerbates other human impacts on biodiversity, such as land use change or pollution (Cramer *et al.*, 2014). Understanding the interactions among the different elements of global change, vegetation distribution and the services provided by ecosystems to humanity are some of the major research challenges of the twenty-first century (Hughes, 2000; Sala *et al.*, 2000; Thuller, 2007; Franklin *et al.*, 2016). Scientists have "high confidence that global temperatures will continue to rise for decades to come, largely due to greenhouse gases produced by human activities" (Stocker *et al.*, 2013). Some human-induced factors (called forcings) that affect climate are global in nature, while others differ from one region to another (Stocker *et al.*, 2013). Accordingly, consequences of climate change on ecosystems differ across regions, vary over time and are expected to be larger in developing than in developed countries (Thomas *et al.*, 2008).

Several global meta-analyses (Parmesan and Yohe, 2003; Root *et al.*, 2003, 2005; Rosenzweig *et al.*, 2008; Poloczanska *et al.*, 2013) have provided overviews on the fingerprints of climate change impacts across natural systems (Parmesan *et al.*, 2013). These fingerprints are biological trends (e.g significant range shifts, advancement of spring phenological events, community (abundance) changes) observed in line with climate change predictions. In books (Hannah, 2010; Newman *et al.*, 2011; Post, 2013) and primary research studies, there is ample evidence showing significant changes observed at species, population, community and ecosystem levels. An increase in the net terrestrial ecosystem productivity has been observed. Most studies hypothesize that the main driver of this trend originates from rising CO_2 through stimulation of photosynthesis (Ramakrishna *et al.*, 2003). Similar trends are observed in the case of biomass, soil carbon stocks (Cramer *et al.*, 2014), and evapotranspiration (Wang *et al.*, 2010) in the terrestrial ecosystem; these are vulnerable due to rising temperature, drought and fire projected for the 21th century. As the report by Settele *et al.* (2014) has summarized, “Species respond to climate change through genotypic adaptation and phenotypic plasticity; by moving out of unfavorable and into favorable climates; or by going locally or globally extinct” (Dawson *et al.*, 2011; Bellard *et al.*, 2012; Penuelas *et al.*, 2013). Species range shifts (Williams *et al.*, 2007; Burrows *et al.*, 2011; Chen *et al.*, 2011) go along with changes in species abundances (Jiguet *et al.*, 2010; Mair *et al.*, 2014), which can effect ecosystem services when they affect pollinators or vectors for various diseases (Zarnetske *et al.*, 2012). Among all of the different impact pathways in which climate change exerts influence on the functioning of ecosystems, phenological shifts are perhaps the most widespread and most studied. Phenological changes were observed during the last decades among plants, fungi and animals (Fitter and Fitter, 2002; Menzel *et al.*, 2006; Kauserud *et al.*, 2010; Ge *et al.*, 2015). Numerous studies document an earlier spring by about 2.3 to 5.2 days/decade in the last 30 years in response to recent climate warming (Parry *et al.*, 2007). Such observations are crucial to be further investigated because of their role in the evolutionary response to recent climate change (Bradshaw and Holzapfel, 2008).

1.2 Introduction to phenology

A brief history of phenology

The word *phenology* originates from the Greek expression “phaino”, which means “to appear” (Demarée and Rutishauser, 2009). Examples of phenological events (phenophases) include growth stages of various living organisms’. These events are repeated year after year, which constitute the seasons of the year (Stoller, 1956; Lieth, 1974). Phenological events include, for instance, the date of the emergence of leaves and flowers, the date of leaf colouring of deciduous trees, the first flight of butterflies, the first appearance of migratory birds or the dates of egg-laying of birds and amphibians. The documentation of growth stages of living organisms has a long tradition, which recently gained new importance regarding climate change research and environmental awareness (Demarée and Rutishauser, 2009). Phenology, *the timing of seasonal activities of animals, plants and fungi*, is “the simplest process in which to track changes in the ecology of species in response to climate change” (Parry *et al.*, 2007).

A complete overview on the history of phenological observations is given by Puppi (2007), starting from the oldest written records originating from China until the Renaissance in the European society. Among others, the contribution of C. von Linné (1707–1778) to phenology must be highlighted. He investigated nature in many aspects; for instance, he documented observations on the effect of climatic factors on plants for decades. Furthermore, temporal patterns of flower opening and closure within a day are known as Linné's floral clock (Frund *et al.*, 2011). R. A. F. de Réaumur (1683–1757) formalized the relation in mathematical terms (1735), when the sum of the temperatures of the previous months reaches a certain value as the day of the year when flowering takes place. After Linnaeus, the development of phenological monitoring networks followed, mostly organized by services or societies that dealt with meteorology or geography (Puppi, 2007). A. Quetelet (1796–1874) established the first phenological network for observations of periodic events and published a guide for the methodology of observations in 1849. C. Morren (1807–1858) used the term *phenology* for the first time in a paper (1852) entitled "Phenological memories of the winter 1852–1853" (in French) in which he recorded extraordinary events, such as second flowering. The first phenological map was made by H. Hoffmann, the founder of the European Phenological Network in 1881 (Puppi, 2007). In Europe, the most important network, the International Phenological Gardens (IPG) (Chmielewski *et al.*, 2013) was founded in 1957. Bruns *et al.* (2003) recommended the establishment of the BBCH system (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie), which is used to standardize phenological growth stages of plants (Meier, 2001; Meier *et al.*, 2009).

In the meantime in America, H. D. Thoreau was the first to conduct systematic observations of phenophases, starting in 1852; later he became known as the father of phenology (Stoller, 1956). Shortly affter, in 1889, A. D. Hopkins (1857–1948) formulated the relationship of elevation, latitude and longitude to seasonal events such as the coming of spring. The relationship was named "Hopkins Law of Bioclimatics". The first extensive phenological observation network in the USA began in the late 1950s with an agricultural focus to improve predictions of crop yield. J. M. Caprio began the first of these projects in 1956; it eventually included around 2,500 volunteer observers distributed throughout 12 states of the USA (Schwartz, 2008).

In England, R. Marsham (1708–1797) is known as the *father of phenology*, since he started his observations for the first time in 1736. Other known recorders (Tookey and Battey, 2010) are G. White (1720–1793) and W. Markwick (1739–1812), whose pioneer work was continued by the establishment of the national network in 1875.

In Hungary, the oldest phenological observations are related to an ancient, but still ongoing tradition in Kőszeg that people drawing the new sprouts of common grapevine (*Vitis vinifera* L.) to a book, called "A szőlő jövésének könyve" (The Book of the "Grape's Coming") on the day of Saint George since 1740. There is a similarly long-term (1851–1994), however nationwide dataset about the flowering times of black locust (*Robinia pseudoacacia* L.) based on foresters' and beekepers' observations (Walkovszky, 1998). There are also several shorter or longer phenological datasets about other plant species in Hungary (Csecserits and Czúcz, 2008). Following these sporadic and fragmented efforts, A. Réthly (1879–1975) called for a more systematic nationwide network of plant phenological observations in 1936 (Réthly, 1936). Following his advice, the Hungarian Meteorological Service organized the national phenological observation network in 1952 (see Chapter 2.2 for more information), which unfortunately fall apart due to lack of funding in 2000 (Dunay, 1984; Szalai *et al.*, 2008). Fortunately, not all phenological observation have disappeared from Hungary; several modern naturalists persevered, and still persevere. The most important recent, 'private' phenological datasets include the works of Szaniszló Priszter, Miklós Galántai, and Zoltán Hámori (Csecserits and Czúcz, 2008; Isépy and Szabó, 2011).

Since the 1960's, new operating observation networks have been established all over the world, which provide long-term historical datasets for recent bioclimatological studies. Details about further phenological data collection methods are given in Chapter 1.3. But beforehand, let me give an overview on the main drivers and feedbacks of phenological events in the upcoming passage.

Drivers and feedbacks of phenology

In most climatic zones of the world, there are seasons characterized by different combinations of environmental factors, which may directly regulate the timing of phenological events, or they may act as cues that set the organisms' internal *biological clock* (Forrest and Miller-Rushing, 2010). Growth stages of plants therefore reflect environmental conditions, genetic factors and the characteristics of the climate (Koch *et al.*, 2009a). Therefore, phenophases can be used as biological indicators of climate change (Donnelly *et al.*, 2004; Koch and Scheifinger, 2004). Several signs for the consequences of climate change are currently observed wordwide. For instance, in Europe it is shown that the phenological events of spring/summer are advancing at an average of 2.5 days per decade (1971-2000) (Menzel *et al.*, 2006). These tendencies are shown for various plant and animal taxa across several regions (Settele *et al.*, 2014) of the Northern (Schwartz *et al.*, 2006; Gordo and Sanz, 2010) and Southern Hemisphere (Chambers *et al.*, 2013). Such patterns of responses are neither uniform nor universal; and the causes of common patterns are still undiscovered (Wilczek *et al.*, 2010).

Differences in phenological patterns originate from certain levels of variability (after Diez *et al.*, 2012). At individual level, plant age and the position of the branches (axillary vs. terminal) are causes for the variation in flowering time. Among individuals (within species), the following factors were identified (Diez *et al.*, 2012) as reasons for variability so far: (i) spatial variation in environmental conditions (e.g. cumulative degree days, thawing degree days, vernalisation, soil moisture, drought index, snowmelt, soil temperature), (ii) resource availability (plant size, availability of stored vegetative resources), (iii) damage (cotyledon or leaf damage, pathogen infection), (iv) genotype and its interaction with the environment and (v) neighborhood density. While among populations, (i) history of natural selection in response to environmental cues, (ii) elevation or aspect, (iii) presence of invasive species, (iv) temperature or vernalisation, (v) photoperiod and temperature interaction, (vi) mating system and (vii) abundance seem to be driving factors (Diez *et al.*, 2012). It is known that various phenophases and plant species respond differently to various environmental factors (Defila and Clot, 2001). Among species, the following factors were shown (Diez *et al.*, 2012) as reasons for variability: (i) native vs. exotic species, (ii) duration of flowering, (iii) photoperiod, (iv) traits (fleshy vs. non-fleshy fruits, pollination syndrome, seed mass, plant size) and (v) phylogenetic relatedness, but with unknown underlying cause. And finally, these drivers were described among communities: (i) disturbance or habitat type, (ii) rainfall, (iii) geographic effects (altitude per temperature, latitude, photoperiod) and (iv) seasonal variation in rainfall and temperature in tropical dry forests and rain forests (Diez *et al.*, 2012).

Phenological events do not only have drivers but also interactions on a multiple scale (as shown in Figure 1.1). Such interactions tend to have feedback to the weather (short term) and climate (long term) system (Penuelas *et al.*, 2009; Richardson *et al.*, 2013; Franklin *et al.*, 2016) occuring on a time scale ranging from minutes (e.g. transpiration) to centuries (e.g. species distribution; Morisette *et al.* (2009)). These feedbacks affect a wide range of ecological processes, including species interactions (Memmott *et al.*, 2007; Yang and Rudolf, 2010; Rafferty *et al.*, 2015; Thackeray *et al.*, 2016), species demography (Miller-Rushing *et al.*, 2010), species distribution (Bertin, 2008; Chuine, 2010) and success of exotic species against native ones (Wolkovich *et al.*, 2013). All of these influences have evolutionary consequences (Forrest and Miller-Rushing, 2010; Gienapp *et al.*, 2014; Johansson *et al.*, 2015) since organisms respond to climate change via accli-

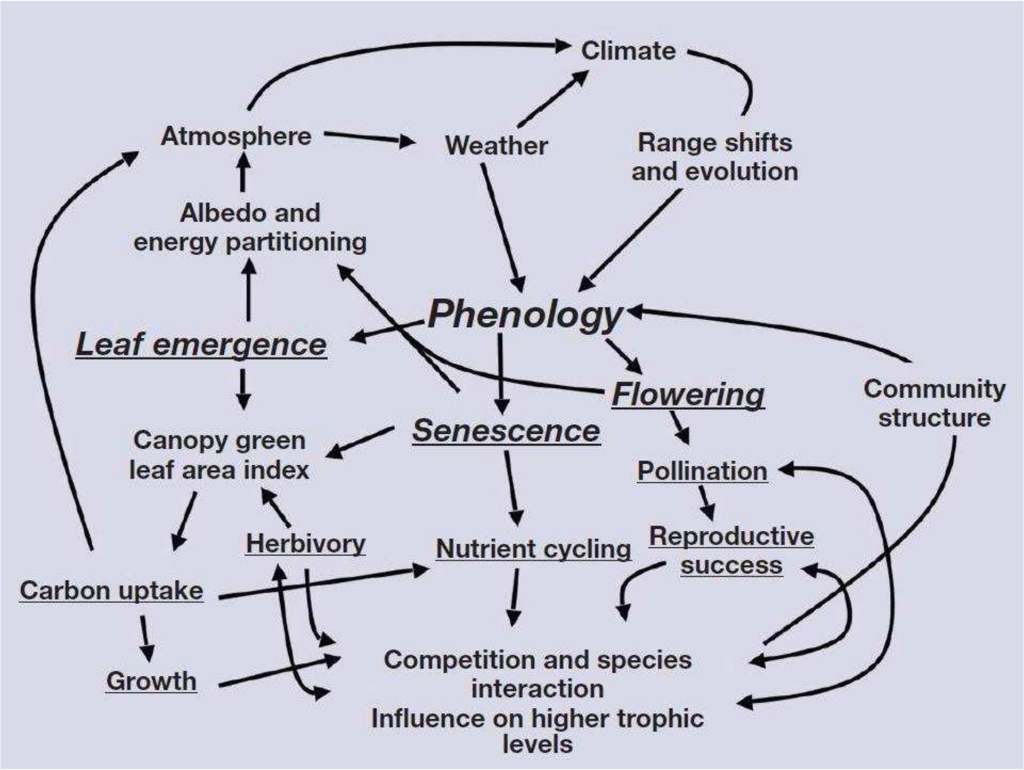

Figure 1.1: Conceptual model showing some of the ways in which plant phenology in temperate climates is intricately linked to variation in weather (short term, days to weeks) and climate (long term, years to centuries), feeds back to the atmosphere and climate system, and influences ecological interactions at multiple scales (individual to community to ecosystem) and trophic (producers to consumers) levels. Underline denotes ecosystem services from which management or economic benefits are derived (Morisette *et al.*, 2009).

mation (Hofmann and Todgham, 2010) and adaptation (Gienapp *et al.*, 2008).

Several consequences of these feedbacks have already been described. For instance, Cleland *et al.* (2012) showed that those plant species that phenologically track climate change tend to experience performance (biomass, percent cover, number of flowers, or individual growth) increases, whereas those that do not track it tend to experience performance declines. Similarly, an analysis (Moller *et al.*, 2008) of phenological trends of one hundred breeding bird species demonstrated that species that did not advance their spring migration declined in abundance (1990–2000), whereas those species that did, tended to demonstrate stable or increasing populations. Furthermore, a field survey from Colorado, using a quantitative genetic experiment (Anderson *et al.*, 2012) estimated a response to selection of 0.2 to 0.5 days acceleration in flowering per generation, which could account for more than 20 per cent of the phenological change observed in the long-term (1973–2011) dataset. Vanasch *et al.* (2013) also demonstrated selection for delayed egg-hatching in response to climate change, which reduced asynchrony between winter moths and their food plant. The number of such examples is growing; therefore, a unified framework, proposed by Visser *et al.* (2010), is needed. It integrates approaches of different disciplines (the view of evolutionary ecologists, physiologists, chronobiologists, and molecular geneticists) to explain phenological events.

1.3 Research directions in phenology

As in every dinamically developing field of science, there are several main research directions in phenology as well. Based on my own experience gained from the study of this field, I have categorized the following research areas of phenology (depicted in Figure 1.2), which provide a framework for the upcoming Chapters.

Detection of past climate change impacts

Statistical analysis plays a major role in climate change detection (Lee *et al.*, 2005) and impact studies. In order to detect causes and consequences of variation in phenology, researchers require tremendous amount of data from large areas of the world. Various methods of phenological data collection providing a data source for this purpose (Fitchett *et al.*, 2015) have been recorded since the first observation. These methods are briefly overviewed in the following paragraphs.

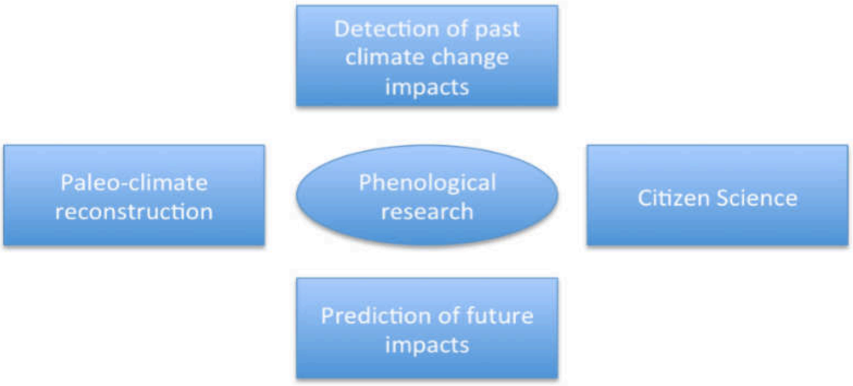

Figure 1.2: Main research directions in phenological research.

The predominant approach to phenological data collection is ground-based recording of the timing of annually recurrent events for a particular species and location (Fitchett *et al.*, 2015). Such phenological observations have been carried out routinely for over 50 years by professionals and different governmental and non-governmental organisations in most European countries (Nekovár *et al.*, 2008; Scheifinger and Templ, 2016).

The COST 725 Action* collected and established a reference (1971–2000) phenology database from these observations (Nekovár *et al.*, 2008; Koch *et al.*, 2009b,c). An analysis of this database provided the most comprehensive study about phenological shifts matching climate change (Menzel *et al.*, 2006). The study highlighted that 78% of all leafing, flowering and fruiting records shifted earlier (30% significantly) and only 3% delayed in response to warming temperature in Europe (Men-

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*The COST 725 Action titled: Establishing a European phenological data platform for climatological applications.

zel *et al.*, 2006). As a successor of the COST 725 Action, the PEP 725[†] project aims to maintain and extend the Pan European Phenological (PEP 725) Database[‡] with an open, unrestricted data access for science, research and education. Ideally, many more scientific articles (Menzel *et al.*, 2006; Duputie *et al.*, 2015; Rodriguez-Galiano *et al.*, 2015; Wang *et al.*, 2016) further Bachelor and Master theses about the analysis of the PEP725 or similar databases will be published.

The increasing number of publications indicates that phenological data have rapidly become a valuable source for impact studies since trends of such observations are known as fingerprints (Parmesan and Yohe, 2003; Root *et al.*, 2003) and biological indicators (Donnelly *et al.*, 2004; Koch and Scheifinger, 2004) of climate change. In Chapter 2 and Chapter 3 such databases (established by the thesis author) have been analysed to detect impacts of climate change in Hungary (Szabó *et al.*, 2016)[§] and across biogeographical regions of Europe (Templ *et al.*, 2017).

One subtype of such long-term (over many years) ground-based observations is recorded by non-professionals called citizen scientists (Bonney *et al.*, 2009; Dickinson *et al.*, 2012). The role of citizen scientists in phenological research is discussed in Chapter 6.

Another type of data source is originating from phenological experiments. These provide short-term phenological observations made in an environment where the environmental factors are controlled to simulate and study the effect of climatic drivers, such as climate extremes (Jentsch *et al.*, 2009; Wolkovich *et al.*, 2012) on phenological events. On the other hand, a comparison of observational studies and warming experiments including four continents and 1634 plant species showed

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[†] `http://www.pep725.eu`

[‡] The thesis author led the development of a manuscript about this database to be published in *Scientific Data* as **Templ, B.**, Scheifinger, H., Hubner, T., Koch, E., Paul, A., Ungersbuck M. and 22 European Partners: PEP 725 – Pan European Phenological Database.

[§] Szabó, B. is the maiden name of Templ, B.

(Wolkovich *et al.*, 2012) that climate experiments may not reflect species' responses to climate change in nature; therefore, the combination of data sources is required.

The emergence of satellite remote imaging in the 1970's and the development of Advanced Very High Resolution Radiometer (AVHRR) technology in 1981 (Fitchett *et al.*, 2015) are additional approaches towards studying phenological responses to climate change and became available through the measuring of leaf reflectance (Stoeckli and Vidale, 2004). Since 2000, AVHRR has increasingly been replaced by higher spatial resolution MODIS (Moderate Resolution Imaging Spectroradiometer) imagery (Zhang *et al.*, 2003), with the Enhanced Vegetation Index (EVI) replacing the Normalized Difference Vegetation Index (NDVI) (Penuelas *et al.*, 2004; Pettorelli *et al.*, 2005).

Digital repeat photography (Sparks *et al.*, 2006; Sonnentag *et al.*, 2012) and herbarium records in biological collections (Robbirt *et al.*, 2011; Molnár *et al.*, 2012; Rawal *et al.*, 2015) are among the most recent additions to the range of methods used in phenological data collection; these methods also provide a valuable source for the detection of climate change impacts.

Prediction of future impacts

One of our challenges is the question of how to synthesize the growing list of observations (overviewed in Chapter 1) indicating the influences of climate change in order to enable the prediction of where, when and which changes will occur (Montoya and Raffaelli, 2010; Pettorelli, 2012). This is very imprtant because the "uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are large (*high confidence*)" (Field *et al.*, 2014). In this section, I intend to highlight the ways of how the timing of phenological events play a key role in the life of humans.

In agriculture and horticulture, phenological observations have a long tradition and importance since many management decisions and the timing of field works (planting, fertilizing, irrigating, crop protection etc.) are based on plant development (Chmielewski, 2013). Crop phenology prediction is a growing research field since the 1980's (Hodges, 1990) because an earlier start of crop flowering and maturity has been documented in recent decades (Craufurd and Wheeler, 2009). These changes led to the trend that the farmers' activities (sowing, harvesting) also occur earlier, which indicates a change (i) in crop season length (Menzel *et al.*, 2006), (ii) in farm management practices, and (iii) introduction of new cultivars – which can produce the same yield (Craufurd and Wheeler, 2009). Phenological data can support management (e.g. effective timing of herbicide and fungicide spraying) and conservation (predictions of species vulnerability) needs, as summarized by Rosemartin *et al.* (2014), the effective timing of herbicide and fungicide spraying.

Plant-pollinator interactions are critical components of a healthy ecosystem. However, these interactions are at risk due to potential phenological mismatches that may disrupt the timing of successful pollination (Solga *et al.*, 2014). On the other hand, there are examples, which do not confirm the occurance of mismatches in plant-pollinator interactions. Bartomeus *et al.* (2011) have found that phenological changes in bees have paralleled changes (over the past 130 years, based on observations from North-America) with the plants that they visit. An experimental study from Gezon *et al.* (2016) has shown (based on snow removal vs. control treatments) that plants face tradeoffs between pollination services and susceptibility to frost damage. Therefore, climate change may constrain the success of early-flowering plants not through plant-pollinator mismatch but through the direct impacts of extreme environmental conditions (Gezon *et al.*, 2016). Not only bees but also beekeepers face challenges world-wide since several predators, parasites and pathogenes affect honeybees. As the phenological responses of plants are species-specific and affected by local environmental conditions, beekeepers must track local flowering schedules and regularly monitor hive conditions (Gupta *et al.*, 2014).

Phenology has a direct importance for cultural ecosystem services as well. In Japan, “hanami” (flower viewing) is the centuries-old practice of picnicking under a blooming cherry tree (*Prunus sp.*). Since AD 812, people enjoy the view and record the first flowering dates of sakura, which became part of the Japanese art and culture (Aono and Kazui, 2008).

Solely in Europe, even more people, circa 150 million, are affected by another phenological event, namely the start of the pollen season. Allergy is the most common chronic disease in Europe. It is known to be triggered by environmental allergens, such as pollen grains from a variety of plants. Accurate prediction of pollen emission (start of allergy season) is an important service, which, we think (Scheifinger *et al.*, 2016), can be improved through enhanced model input (e.g. real-time phenological data).

Changes in climate may result in changes in population growth rates of agriculturally important insects. These result in (i) increases in the number of generations, (ii) extension of the development season, (iii) changes in crop-pest synchrony, (iv) changes in interspecific interactions, and (v) increased risk of invasion by migrant pests (Porter *et al.*, 1991; Thomson *et al.*, 2010). Therefore, timely and reliable models are required to understand and predict the dynamics of insect populations in agroecosystems (Strand, 2000). Phenological observations of plants are related to this issue as well since they (e.g. flowering time) can be used to predict insect activity (Herms, 2004) via the tracking of degree-day[¶] accumulation. In Chapter 4, an attempt to predict flowering time is introduced, which can later be extended to any other phenological event. Our results (Templ *et al.*, 2016), obtained by

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[¶] Degree-days are the sum of daily mean temperatures expressed in degrees that can be accumulated above a particular temperature threshold to provide a sum of (growing) degree days over a period (Cleland *et al.*, 2007).

survival modelling, provide an improved prediction of flowering time compared to traditional regression methods.

Paleoclimate reconstruction

In paleoclimatology, or the study of past climates, scientists use what is known as proxy data to reconstruct past climate conditions. These proxy data are "preserved physical characteristics of the environment, can be gathered from natural recorders of climate variability such as tree rings, ice cores, fossil pollen, ocean sediments, corals, shells and microfossils" (Masson-Delmotte *et al.*, 2013), and plant phenophases. Paleoclimatologists apply a wide variety of techniques to determine climatic conditions before the global record-keeping began in the 1880's.

Several studies used a combination of different types of proxy data (tree rings, sediments, ice cores) for the reconstruction of historical climate changes (Jones *et al.*, 1988; Mann *et al.*, 1999). They also refer to plant phenophases as indicators of climate change or proxies for temperature (Menzel, 2002, 2003; Miller-Rushing *et al.*, 2008), especially when the timing of the phenological event is closely related to specific climatic conditions during plant development (Sparks *et al.*, 2000; Aono and Kazui, 2008). In Kyoto (Japan), phenological data series for the cherry tree (*Prunus serrulata* Lindl.) have been recorded in old diaries and chronicles since the 9th century. Aono and Kazui (2008) used these records and successfully reconstructed spring temperature. Another observation, famous for its length and originating from England, is known as Marsham's phenological data (Margary, 1926). Sparks and Carey (1995) re-discovered these data and predicted changes for the future timing of phenological events. In contrast, Lauscher and Lauscher (1981) used leafing dates of the chestnut tree, observed in Geneva (Switzerland) since 1808 to show climatic warming. Temperature reconstruction, beginning in the 16th century, was done by Maurer *et al.* (2009) using grape harvest dates recorded in Vienna and Klosterneuburg (Austria). Similarly, Kiss *et al.* (2010) made a reconstruction of May-July temperatures possible by using multi-proxy data (vine and grain) documented in Köszeg (Hungary). In Chapter 5, the usage of flowering data as temperature proxy is discussed based on our sensitivity study (Lehoczky *et al.*, 2016).

Citizen science

Observations of amateur naturalists have been important for centuries, while citizen science projects proliferated into hundreds of various disciplines solely in the past decade. These projects are mostly focused on ecological questions, for instance the monitoring of biodiversity (Wildlife Sightings[‖]), weather (Old Weather[**]), palaeontology (Paleo Quest[††]) and phenology (USA National Phenology Network (USA–NPN),[‡‡] and many others). In this Chapter (1.3), the connection between phenology and citizen science is discussed.

Astronomy and ornithology have the largest body of amateur experts and the longest history of engaging volunteers in scientific research. In recent years, sophisticated internet applications effectively utilize crowdsourcing for data collection across large geographic regions, offering opportunities for participants to provide, gain access to, and make meaning of their collective data. Today, public and professional ecologists alike have access to a growing number of tools to explore changes in phenology, relative abundance, distributions, survival, and reproductive success of organisms across time and space. In the process, citizen science has influenced both the scale of ecological research that is being done and the relationship between ecologists and the public (Dickinson *et al.*, 2010; Kobori *et al.*,

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[‖] `http://http://www.wildlifesightings.net`

[**] `https://www.oldweather.org`

[††] `http://www.paleoquest.org`

[‡‡] `http://https://www.usanpn.org`

2016). Silverton (2009) mentions three factors responsible for “this great explosion of activity” in citizen science: (i) easily available technical tools for disseminating information about projects and gathering data from the public, (ii) the increasing realization among professional scientists that the public represents a free source of labour, skills, computational power and even finance, and (iii) project related science outreach possibly benefiting citizen science. Undoubtedly, the best way for the public to understand and appreciate science is to participate in it.

As it was discussed before (Chapter 1.2), traditional phenological data collection has always relied on observers, operated by national meteorological and hydrometeorological services (Scheifinger and Templ, 2016). This has been challenged by several factors, which caused a significant drop of phenological observations in Europe (Nekovár *et al.*, 2008). In the meantime, people are getting more and more dependent on electronic devices, which may open another era for ecological monitoring. There are existing examples where such new technologies facilitate ecological data collection enormously, for example through mobile applications, social media, education programs, webcams, and even drones.

We have already published the possible ways of how citizen science technologies could be implemented in the monitoring systems of national meteorological and hydrometeorological services (Scheifinger and Templ, 2016). These aspects and our vision for the future of the European phenological networks can be found in Chapter 6.

1.4 Outline of the thesis

This PhD thesis is principally dedicated to applications and new developments of phenological research. In total, research results of five scientific papers (four original research articles and one viewpoint article) are included in this thesis; three of them with first authorship and the other two with co-authorship of this author. Four of the papers are already published/online first articles and one is accepted for publication in international journals.

According to the research directions in phenology outlined in Chapter 1, the following two Chapters focus on the detection of climate change impacts. In **Chapter 2**, observed trends and influences of climate on flowering phenological records for six plant species are introduced based on observations from the Hungarian Meteorological Service recorded between 1952 and 2000. The paper[‡] **Szabó, B.**, Vincze, E. and Czúcz, B. (2016) "Flowering phenological changes in relation to climate change in Hungary" is published in *International Journal of Biometeorology*, 60: 1347–1356; doi: 10.1007/s00484-015-1128-1. Impact factor: 2.309.

Chapter 3 focuses on the description of spatio-temporal patterns of flowering time across biogeographical regions of Europe, based on data (1970–2010) that were collected from twelve countries along a 3000 km long transect from northern to eastern Central Europe. The manuscript **Templ, B.**, Templ, M., Filzmoser, P., Lehoczky, A., Bakšienė, E., Fleck, S., Gregow, H., Hodzic, S., Kalvāne, G., Kubin, E., Palm, V., Romanovskaja, D., Vučetič, V., Žust, A., Czúcz, B. and the NS-Pheno Team (2017) "Phenological patterns of flowering across biogeographical regions of Europe" is accepted (19.01.2017) in the *International Journal of Biometeorology*, doi: 10.1007/s00484-017-1312-6. Impact factor: 2.309.

[‡] The thesis author was nominated and became the winner of the European Meteorological Society (EMS) Tromp Award 2016 for this paper. The Tromp Foundation is funding this award with the intention to promote biometeorology in Europe, as a recognition for outstanding achievements in biometeorology.

The aim of **Chapter 4** is related to another research direction (prediction of future impacts) discussed in Chapter 1. We tested the predictive power of Cox hazards models in phenological research, in order to calculate the hazard ratio of different climate variables and to show their influence on the "risk" of flowering time. The paper **Templ, B.**, Fleck, S., Templ, M. (2016) "Change of plant phenophases explained by survival modelling" is accepted for publication (already Online first published) in *International Journal of Biometeorology*, doi: 10.1007/s00484-016-1267-z. Impact factor: 2.309.

Chapter 5 discusses one potential application of phenological data, namely for paleoclimate reconstruction. It is another important research field outlined in Chapter 1. We evaluated the accuracy of the usage of plant phenophases as proxies for temperature estimations. The paper Lehoczky, A., **Szabó, B.**, Pongrácz, R., Szentkirályi, F. (2016) "Applicability of flowering onset time series for a proxy of temperature – based on Transylvanian phenological observations from the 19th century" is published in *Applied Ecology and Environmental Research*, 14: 213–233; doi: 10.15666/aeer/1402–213233. Impact factor: 0.557.

The last **Chapter 6** related to citizen science, another field of phenological research outlined in Chapter 1. It discusses potential solutions to rebuild and maintain phenological observation networks in Europe. The paper is a viewpoint article, published as Scheifinger, H. and **Templ, B.** (2016) "Is citizen science the recipe for the survival of paper-based phenological networks in Europe?" in *BioScience*, 66: 533–534; doi:10.1093/biosci/biw069. Impact factor: 4.294.

CHAPTER 2

Flowering phenological changes in relation to climate change in Hungary*

Abstract

The importance of long-term plant phenological time series is growing in monitoring of climate change impacts worldwide. To detect trends and assess possible influences of climate in Hungary, we studied flowering phenological records for 6 species (*Convallaria majalis*, *Taraxacum officinale*, *Syringa vulgaris*, *Sambucus nigra*, *Robinia pseudoacacia*, *Tilia cordata*) based on phenological observations from the Hungarian Meteorological Service recorded between 1952 and 2000.

Altogether 4 from the 6 examined plant species showed significant advancement in flowering onset with an average rate of 1.9–4.4 days per decade. We found that it was the mean temperature of the 2–3 months immediately preceding the mean

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*The paper is published in the *International Journal of Biometeorology* (Szabó *et al.*, 2016) and is co-authored with Enikő Vincze and Bálint Czúcz.

flowering date, which most prominently influenced its timing. In addition, several species were affected by the late winter (Jan–Mar) values of the North Atlantic Oscillation (NAO) index. We also detected sporadic long-term effects for all species, where climatic variables from earlier months exerted influence with varying sign and little recognizable pattern: the temperature / NAO of the previous autumn (Aug–Dec) seems to influence *C. majalis*, and the temperature / precipitation of the previous spring (Feb–Apr) has some effect on *T. cordata* flowering.

2.1 Introduction

There is a worldwide increase in the number of studies, which call attention to the ecological consequences of global climate change. These effects appear at population, community, as well as ecosystem levels by modifying species composition, spatial patterns and ecosystem functioning (Parmesan, 2006; Root *et al.*, 2003; Rosenzweig *et al.*, 2008). Shifts in the timing of recurring life history events (phenophases) of species constitute a major component of the ecological impacts of climate change (Parmesan and Yohe, 2003; Walther *et al.*, 2002). Diverging phenological shifts in communities may lead to a breakdown of synchronous species interactions (Buse *et al.*, 1999; Stenseth *et al.*, 2002), which eventually can result in increased risk of extinctions (Memmott *et al.*, 2007). Several studies warn about potentially detrimental impacts of these processes (Both *et al.*, 2009; Visser and Both, 2005). Furthermore, phenology also exerts control over many potential feedbacks from vegetation to the climate system by influencing the seasonality of albedo, canopy conductance, fluxes of water and energy, CO_2 and biogenic volatile organic compounds (Richardson *et al.*, 2013).

The analysis of long-term plant phenological time series have been in the focus of climate impact research since the early 1990s (Schwartz, 1999). Several studies have demonstrated significant advancements in spring phenophases of plants across the Northern Hemisphere (Menzel *et al.*, 2006; Schleip *et al.*, 2009; Schwartz *et al.*, 2006). Similar tendencies can be seen across several other taxonomic groups, including e.g. fungi (Kauserud *et al.*, 2010), insects (Robinet and Roques, 2010), amphibians (Beebee, 2002), and birds (Gordo, 2007). These changes are not limited to terrestrial ecosystems but can also be observed in freshwater and marine systems (Thackeray *et al.*, 2010).

Induction of different phenophases along the lifecycle of individuals are governed by species-specific environmental thresholds. Alterations in CO_2 level, temperature, photoperiod, solar radiation, precipitation, snowmelt and frost effects exert influence together on plants' physiological processes (Körner and Basler, 2010; Nord and Lynch, 2009). There are several conflicting reports in the literature about the relative roles of different drivers and/or explanatory variables of the phenological development (Migliavacca *et al.*, 2012). The best predictors of plant phenology within the temperate zone are local meteorological variables, like air temperature and precipitation, but macroclimatic circulation patterns, such as the North Atlantic Oscillation (NAO) index are also frequently considered as predictors. It is also well known that NAO-induced local weather conditions can affect phenology and this relationship can be different in different parts of Europe (Gordo and Sanz, 2010; Scheifinger *et al.*, 2002; Stenseth *et al.*, 2003), as it is expected from this impact system (Hurrel and van Loon, 1997; Pauling *et al.*, 2006; Trigo *et al.*, 2002).

Strongly connected to the problem of identifying the appropriate predictor variables is the problem of finding the effective time period, the weather of which most strongly influences the subsequent phenological events. The timing of flowering is controlled by complex mechanisms, which act to ensure that flower emergence occurs in suitable conditions attuned to seasons (Tookey and Battey, 2010). Most studies report that the flowering phenophase shows the strongest correlation with the average air temperature of a few months preceding the event, but focusing only on spring temperatures can lead to inaccurate interpretations and predictions for species, because photoperiod and vernalisation plays also major roles in spring phenological events (Cook *et al.*, 2012; Körner and Basler, 2010; Tookey and Battey, 2010).

The aim of our study is to evaluate the shift in the flowering phenologies of six spring-flowering plant species in Hungary during the second half of the last century (1952–2000). In spite of the number of phenological time series available, Hungary is a relatively unexplored country in central Europe in terms of phenological studies. Similarly to other parts of western and central Europe, Hungary is relatively warm and springs tend to be drier during positive NAO periods, while wetter than average during negative NAO periods (Bartholy *et al.*, 2009a). In this study we have set two main goals: (i) to test whether trends similar to those observed in other parts of Europe can also be detected within Hungarian spring phenological changes, (ii) to determine which month's climate exerts the greatest effect on the flowering onset of different species.

2.2 Materials and methods

Phenological data

To seek for potential shifts in spring phenological events, we studied the beginning of flowering (BF) of 6 angiosperm species: lily of the valley (*Convallaria majalis* L.), common dandelion (*Taraxacum officinale* W.), common lilac (*Syringa vulgaris* L.), black elder (*Sambucus nigra* L.), black locust (*Robinia pseudoacacia* L.), and small-leaved lime (*Tilia cordata* Mill.) during the period 1952–2000 in Hungary. Historical data on plant phenological observations were obtained from the Hungarian Meteorological Service (Table 2.1). Our selection of species and observing stations was seriously limited by the extreme fluctuation in the number of stations, observers and observed species which characterized the phenology observations of the Hungarian Meteorological Service (Dunay, 1984; Szalai *et al.*, 2008). During 1952–1961 the observation network of the Meteorological Service consisted of 100 stations performing phenological observations on 100 phenological events of 37 plant species. The number of stations decreased to 60 with an increasingly uneven geographical coverage during 1961–1981 (Table 2.1). After a one-year disruption in 1982, the network was reorganized with a drastically reduced list of observed species and phenological events (shifting from wild plant species to crops), and a reduced number of stations with a more even coverage (Dunay, 1984; Szalai *et al.*, 2008). This reorganized network, which was hosted by the regional Pest Control and Agrochemistry stations of the Agriculture and Food Ministry, operated in consistent and reliable way from 1983 until 2000, when the entire network fall apart due to lack of funding. As a consequence of these recurrent reorganizations phenological time series long enough for climate impact analysis can only be studied for a few phenological events, which were observed both prior to and after 1982, and even for these events the number of complete time series is very limited (Table 2.1). Luckily, the definition of phenological events did not change during the reorganizations, so the beginning of flowering phenological event was consequently defined as “the appearance of the first flowers producing pollens on at least 50% of the observed plants” (Dunay, 1984), which equals the event 61, according to the BBCH scale (Meier, 2001).

We converted all dates given in months and days to day of the year (doy) values. To exclude potential coding and typing mistakes we first checked for outliers using the *extremevalues* R package (van der Loo, 2010) assuming a normal distribution. In order to cope with the fluctuations and inhomogeneity in the dis-

Table 2.1: An overview of the phenological observations by the Hungarian Meteorological Service (HMS) for the studied species. For each species and phenophase (BF – beginning of flowering, FL –appearance of first leaves, BR: beginning of ripening, LF: leaf falling) the following three numbers are given: a: the total number of records between 1952-2000; b: the number of stations with at least 10 years of observations before 1982 (the reorganization of the HMS phenology network); and c: the number of stations with at least 10 years of observations after 1982. For each phenophase the corresponding BBCH code (Meier, 2001) is also given in parentheses. The datasets used in our study are marked in bold.

Species	**BF (#61)**	**FL (#11)**	**BR (#86)**	**LF (#97)**
	a (b, c)	a (b, c)	a (b, c)	a (b, c)
Taraxacum officinale	**2012 (62, 20)**			
Syringa vulgaris	**2339 (71, 19)**		1304 (45, 0)	1719 (65, 0)
Convallaria majalis	**2039 (64, 19)**			
Robinia pseudoacacia	**2330 (72, 20)**	1689 (66, 0)	1336 (45, 0)	1850 (67, 0)
Sambucus nigra	**2167 (64, 20)**		1716 (62, 0)	1631 (61, 0)
Tilia cordata	**1729 (51, 20)**	597 (22, 0)	1113 (38, 0)	1381 (54, 0)

tribution of stations, we grouped the observations according to the 6 geographical macroregions of Hungary (Dövényi, 2010). For each region we only kept observation time series of at least 10 years of continuous data. As an additional criterion, we only analyzed data for those regions where there were at least two stations with at least 10 years of continuous data both before and after the reorganization of 1982. This way, we compiled regional datasets for three geographical macroregions (*Alföld* – Great Hungarian Plain, r1; *Nyugat-magyarországi peremvidék* – West Hungary, r3; and *Dunántúli-középhegység* – Transdanubian Mountains, r5) consisting altogether of 133 local data series of the studied species (see Figure 2.1). To deal with uneven data coverage, we used linear mixed models to derive single homogenized time series as described by Schaber and Badeck (2002). Accordingly, for each species and region, we created time series using a fixed effect of year, with a station-level random effect with the help of the *pheno* R package (Schaber, 2012). Accordingly, the analyses were carried out on 18 homogenized time series for the six species and the three regions (r1, r3, r5).

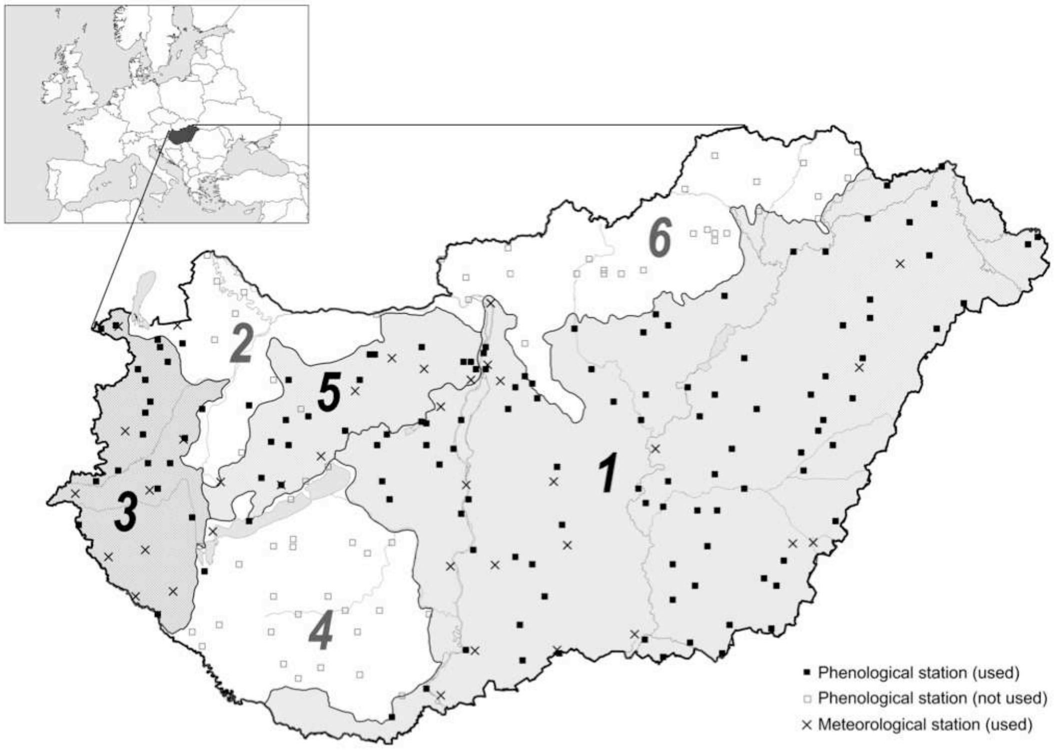

Figure 2.1: The location of the study regions and the data sources. Local observational stations used in our analysis: w: phenological stations; ×: meteorological stations. Abbreviations of the regions: 1: Alföld (Great Hungarian Plain), 3: Nyugat-magyarországi Peremvidék (West Hungary); 5: Dunántúli-középhegység (Transdanubian Mountains). Phenological stations outside the three study regions are also shown in this map, but they were not used in the analysis.

Climate data

To determine any correlations between the macroclimatic conditions and the flowering phenology of the selected species, we generated a large number of climatic variables based on air temperature, precipitation and NAO indices data. As a starting point for generating air temperature and precipitation variables we used monthly records from the Hungarian Meteorological Service. After check for outliers similar to what was done in case of the phenological data we used the same linear mixed model procedure (Schaber and Badeck, 2002) to generate a single homogenized macroclimatic signal for each region (see Figure 2.1).

To identify the combination of climatic variables and effective periods, which effectively influence the spring phenologies of the studied species we used the methodology of Gordo and Sanz (2010). Accordingly, we defined a series of monthly, bimonthly, and trimonthly means (temperature) and sums (precipitation) of climate variables, which could potentially influence the actual phenological event. We created 18 monthly mean temperature (T1) variables relative to the current year: from the previous year‘s January (T101) to current year's June (T118). Similarly, we defined seventeen bimonthly (T2) variables, with T201 meaning the mean temperature of previous year‘s Jan–Feb, T202 being previous year‘s Feb–Mar, and T217 being current year‘s May-June. Trimonthly temperature dataseries (T3) were also created in a similar way, ranging from T301 (previous year‘s Jan–Mar) to T316 (current year's Apr–June). We defined precipitation variables the same way as T, namely 18 monthly (P101–P118), 17 bimonthly (P201–P217) and 16 trimonthly (P301–P316) precipitation sum variables were created.

To check for potential effects of large-scale circulation patterns on the timing of the studied phenological events we also defined predictor variables based on the values of the North Atlantic Oscillation (NAO) index. Based on the monthly NAO values taken from the NOAA Climatic Research Unit homepage [†], we defined 18 variables for monthly (N101–N118), 17 variables for bimonthly (N201–N217), and 16 variables of trimonthly (N301–N316) mean NAO values, exactly following the structure of the other climatological variables. This way we created a set of 153 strongly correlated climatic predictors (51 for temperature, 51 for precipitation

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[†] `http://www.cru.uea.ac.uk/cru/data/nao/`

and 51 for NAO). However, unlike mean temperature and sum of precipitation data (which were constructed for each individual region separately) there was a single common NAO data series for all of the studied regions.

Data analysis

We first computed linear regression coefficients for the time series to assess the magnitude and the significance of the trends in flowering date over time for each species and within each region (Sneyers, 1990).

As a next step, we looked for statistical relationships between the phenological data and the climatic variables. To this end we first removed temporal trends from all of the time series, taking the residuals of the univariate linear regressions fitted in the prevous step as "detrended" phenological variables. After this detrending step, we created separate linear regression models for each species and region. As the set of predictors was still highly intercorrelated, we used forward stepwise selection to sequentially add terms from the set of potential predictors until reaching minimal AIC (Akaike's Information Criterion), a metric commonly applied to compare and rank multiple competing models (Johnson and Omland, 2004). We checked the significance of the parameters from the best models with univariate F tests, adding the terms sequentially to the model in the same order they were found by the stepwise algorithm. We used Bonferroni correction to avoid a potential proliferation of type I errors (Abdi, 2007). All data preparation and statistical analysis steps were performed in the R statistical environment (R Development Core Team, 2015), using the add-on packages *reshape2* (Wickham, 2007), *extremevalues* (van der Loo, 2010), and *pheno* (Schaber, 2012).

2.3 Results

We found significant shifts in flowering onset dates for 4 species (*C. majalis*, *T. officinale*, *S. nigra* and *T. cordata*) in the examined period (1952–2000). All of the trends (even the non-significant ones) were negative (onset of flowering gradually shifting earlier). The strongest advancements (2.8–4.4 days per decade) were found for *T. cordata*. Two of the examined woody species (*S. vulgaris* and *R. pseudoacacia*) did not show significant trends. Altogether 7 of the 18 studied cases (species ×regions) showed significant advancement in their beginning of flowering (Table 2.2).

Table 2.2: Mean dates (a), trends (b) and significance levels in the flowering of the studied species in three regions of Hungary. Trends are expressed as linear regression coefficients (day/year, negative values mean advancement), significance level symbols: ***: $0<p<0.001$; **: $0.001<p<0.01$; *: $0.01<p<0.05$. Relationships found to be significant above $\alpha = .05$ are highlighted in bold.

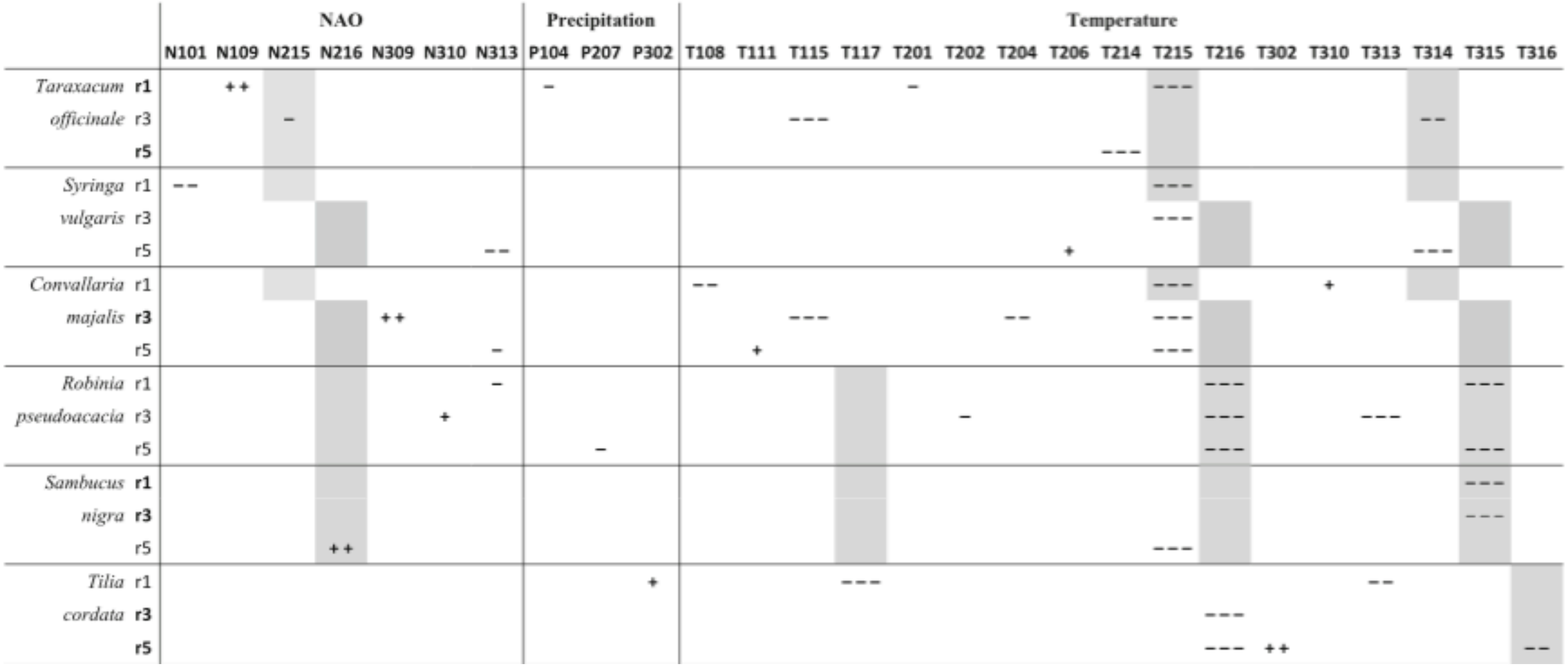
Species	**r1: Great Hungarian Plain**	**r3: West Hungary**	**r5: Transdanubian Mountains**
	a (b)	a (b)	a (b)
Taraxacum officinale	11 Apr (**-0.275****)	12 Apr (-0.08)	11 Apr (**-0.371*****)
Syringa vulgaris	28 Apr (-0.103)	1 May (-0.05)	1 May(-0.043)
Convallaria majalis	29 Apr (-0.024)	2 May (**-0.188***)	2 May (0.073)
Robinia pseudoacacia	17 May (0.011)	22 May (-0.014)	22 May (-0.084)
Sambucus nigra	19 May (**-0.138***)	24 May (**-0.188****)	21 May (-0.137)
Tilia cordata	10 Jun (-0.069)	16 Jun (**-0.442*****)	16 Jun (**-0.279*****)

Altogether we found 45 significant relationships between the timing of the flowering events and the meteorological variables studied (Table 2.3, Figure 2.2). The majority (33) of these relationships were linked to temperature, whereas NAO and precipitation were found in 9 and 3 relationships respectively. For almost all of the studied cases the most influential predictor was the temperature of the 2 or

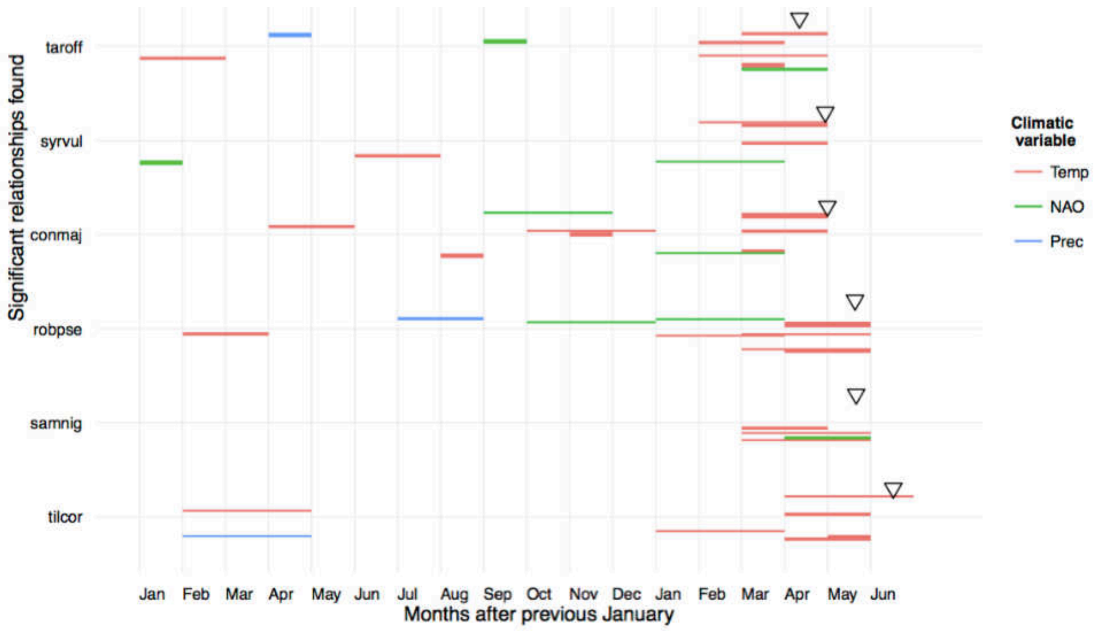
3 months immediately preceding the typical date of the phenological event studied (henceforward called “short term” relationships, Table 2.3). We also found 15 significant “long-term” connections documenting delayed influence of past meteorological conditions. However, these long-term relationships were much weaker, involving all 3 climatic elements (temperature, precipitation and NAO) with very little pattern recognizable. The coefficients for “short-term” temperature and NAO variables were generally negative, indicating that warm years and positive NAO anomalies generally induced earlier flowering onset. On the other hand coefficients for long-term effects greatly varied among species and seasons (Table 2.3, Figure 2.2).

There were only 27 out of the 153 climatic predictors studied that were included in any of the significant relationships identified. The most influential meteorological predictors seemed to be Mar-Apr temperature (T215: *T. officinale*, *S. vulgaris*, *C. majalis*), Apr-May temperature (T216: *T. cordata*) and Mar-May temperature (T315: *R. pseudoacacia*, *S. nigra*). There is also a weak recurrent pattern in the case of NAO, with an effective period at the end of the winter (Jan-Mar, N313), which seems to influence several species (*S. vulgaris, C. majalis, R. pseudoacacia*). As for long term relationships, the temperature / NAO of the previous autumn seems to influence *C. majalis*, and the temperature / precipitation of the previous early spring (Feb-Apr) has some effect on *T. cordata* flowering (Table 2.3, Figure 2.2).

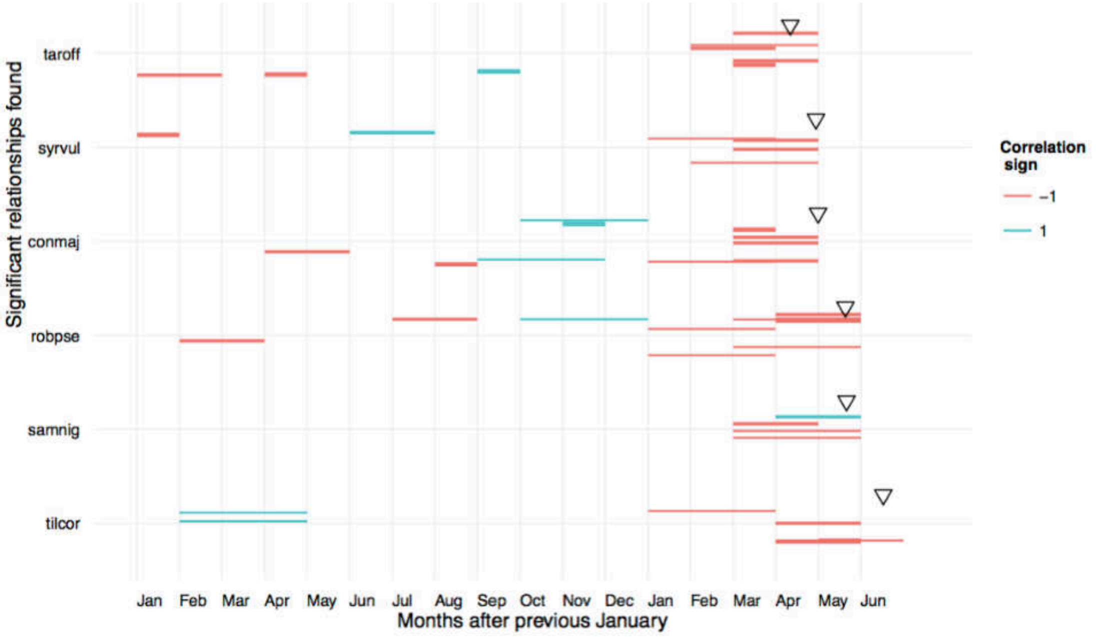
Table 2.3: The highest monthly/bi/trimonthly temperature, precipitation and NAO values influencing flowering phenology according to the results of the forward stepwise variable selection. Climatic variables follow the naming convention introduced and used in the text, the periods ending in the month of the mean flowering date are highlighted by shading; r1, r3, r5: the three study regions (Figure 2.1), regions with significant trends are highlighted in bold; +/−−, ++/−−, + + +/− − −: significant positive/negative relationships at α =0.05, 0.01 and 0.001 respectively.



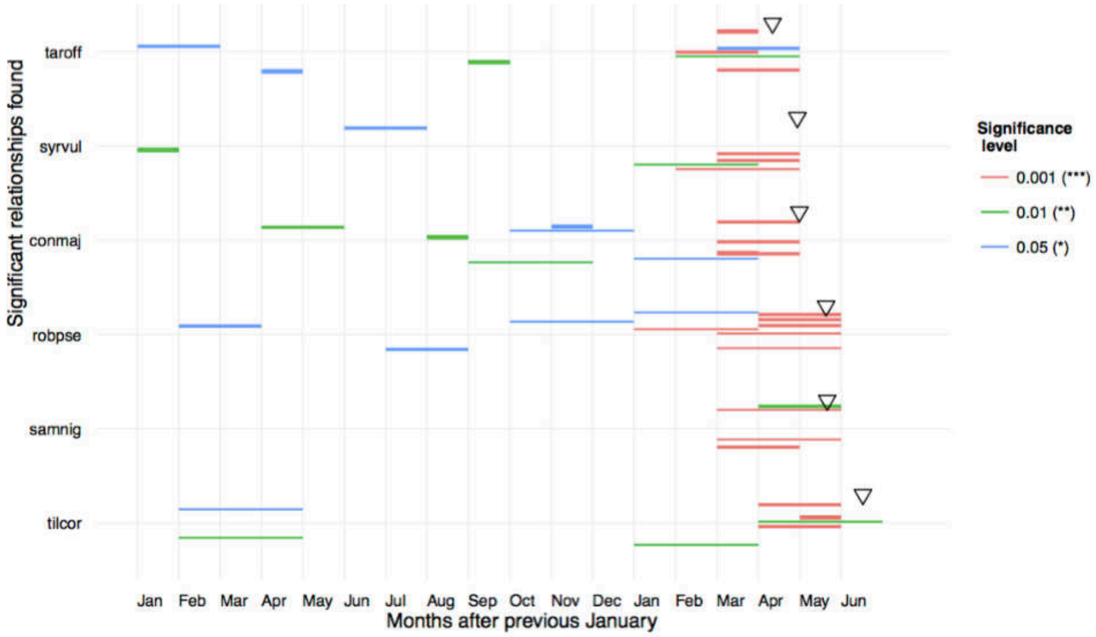
		NAO							Precipitation			Temperature																
		N101	**N109**	**N215**	**N216**	**N309**	**N310**	**N313**	**P104**	**P207**	**P302**	**T108**	**T111**	**T115**	**T117**	**T201**	**T202**	**T204**	**T206**	**T214**	**T215**	**T216**	**T302**	**T310**	**T313**	**T314**	**T315**	**T316**
Taraxacum	**r1**		++						−							−					−−−							
officinale	r3			−										−−−												−−		
	r5																			−−−								
Syringa	r1	−−																			−−−							
vulgaris	r3																				−−−							
	r5							−−											+							−−−		
Convallaria	r1											−−									−−−			+				
majalis	**r3**					++								−−−				−−			−−−							
	r5							−					+								−−−							
Robinia	r1							−														−−−					−−−	
pseudoacacia	r3						+										−					−−−			−−−			
	r5									−												−−−					−−−	
Sambucus	**r1**																										−−−	
nigra	**r3**																										−−−	
	r5				++																−−−							
Tilia	r1										+				−−−										−−			
cordata	**r3**																					−−−						
	r5																					−−−	++					−−



(a) Periods are grouped by species along the vertical axis, and grouped by color according to climatic variable.



(b) Periods are grouped by the direction of the relationship.



(c) Periods are grouped by the significance level.

Figure 2.2: Periods of the climatic predictors significantly influencing the flowering onset of the studied species (*T. officinale, S. vulgaris, C. majalis, R. pseudoacacia, S. nigra, T. cordata*). Periods grouped by climate variables (**a**), the direction of relationship (**b**) and significance level (**c**). Triangles indicate the mean date of the flowering onset in Hungary.

2.4 Discussion

Shifts in spring plant phenological events in the Carpathian Basin (Central Europe) are particularly poorly documented, with a few exceptions coming from the works of Keresztes (1984); Walkovszky (1998); Schieber *et al.* (2009); Molnár *et al.* (2012); Varga *et al.* (2012), and Lehoczky *et al.* (2016). Based on datasets for six plant species, the current paper presents the most in-depth study so far of phenological trends and their environmental drivers among Hungary.

Throughout Europe, the vast majority of spring phenological time series ending after 1988 reveal advancing trends (Dose and Menzel, 2004). We also detected significantly advancing trends in 7 of the studied 18 cases for 4 of the 6 examined species during the second half of the 20th century in Hungary. This ratio is considerably smaller than the findings of Parmesan and Yohe (2003) for the entire Northern Hemisphere, where 87% of the terrestrial datasets exhibited responses coherent with global warming. Askeyev *et al.* (2010) pointed out that phenological changes have been less marked in the eastern part of Europe, than in western and central Europe. This can be one of the possible reasons for not finding significant flowering trends in all of the studied regions and species. Nevertheless, our results also show shifts very similar to the tendencies experienced in other parts of Europe (2.2–2.5 day advance per decade) (Chmielewski and Rotzer, 2002; Menzel *et al.*, 2006).

Similarly to most of the studies exploring the relationship between climatic variables and spring phenological events (Parry *et al.*, 2007), we have found temperature to be the most influential determinant of the timing of flowering in Hungary. All of the most significant ($p < .001$) relationships found belong to temperature from the Jan-May period (Figure 2.2). In most cases, the effective periods are the 2-3 months containing or immediately preceding the month of mean flowering time. This observation is highly supported by other studies as well (e.g. Estrella *et al.*, 2009; Fitter and Fitter, 2002; Sparks *et al.*, 2000).

Beyond question, there are no other meteorological variables and effective periods, which could match the significance of short-term air temperature in shaping the spring phenologies of the studied species. The only exeception is NAO, with a weak effective period at the end of the winter (Jan-Mar, N313), which seems to influence a broad range of plants in Hungary, including earlier and later flowering species (*S. vulgaris, C. majalis, R. pseudoacacia*). In many parts of the world teleconnection indices, like NAO, describing large-scale circulation patterns are considered as a useful proxy for precipitation anomalies (Lopez-Moreno *et al.*, 2011). In Hungary, winter NAO is known to be strongly correlated to both temperature (positively) and precipitation (negatively, Zsilinszki (2014)). It is important to note, however, that being an abstract teleconnection index, NAO cannot directly influence plant physiological processes, probably just indirectly through further unidentified meteorological variables. As we have explicitly added both mean temperature and precipitation to our set of predictors, thus the significant influence of NAO cannot be attributed to either of them as an underlying factor in our case. Consequently, we can assume that there is still a significant, yet unknown meteorological factor (e.g. temperature or precipitation extremities, solar radiation, wind, etc. – see also Gordo and Sanz (2010)) influencing the flowering phenologies of a broad range of taxa, for which Jan-Mar winter NAO values act as a proxy in Hungary.

Even though spring phenologies are known to be highly rainfall-sensitive in many parts of the world (Penuelas *et al.*, 2004), we could not find any clear relationships for precipitation. On the other hand it is known (Fu *et al.*, 2014) that at higher latitudes, the effect of GDD requirement, chilling and precipitation influence the spring vegetation green-up in complex interaction. The simple linear modelling technique applied by us might not be appropriate for capturing such complex responses in general, whereas the few weak but significant long-term relationships involving precipitation (and NAO) might be seen as legacies testifying to the presence of such complex nonlinear relationships.

Taraxacum officinale showed significant phenological trends in 2 of the 3 studied regions for the 1952–2000 period. *T. officinale* exhibits a strong response to the temperature (Feb-Apr,) of the current year, with sporadic additional long term effects (N109, P104, T201). At the European level, *T. officinale* shows a stronger response to temperature in warmer than in colder countries (Menzel *et al.*, 2006). We also documented a relatively high-speed advancement for this species in Hungary (–3.4 - –3.9 days per decade), which fits well into this broader European picture (Menzel *et al.*, 2006; Jatczak and Walawender, 2009).

In the case of *Syringa vulgaris* we did not find any significant shifts, but we demonstrated a temperature (Feb-Apr, T314) and a NAO (Jan-Mar, N313) sensitivity of the flowering onset. There is a known temperature sensitivity of this species across Europe (–2 - –4 days/°C for the mean temperature of the previous months) exhibiting a stronger response to temperature in warmer than in colder countries (Menzel *et al.*, 2006). There are several studies that documented significant shifts of 4–6 days per decade in the flowering of *S. vulgaris* both in Europe (Sparks *et al.*, 2011; Jatczak and Walawender, 2009), and in North America (Schwartz and Reiter, 2000).

Convallaria majalis is one of the species in Europe, which is not really well represented in phenological studies (Nekovár *et al.*, 2008). We have detected a significant trend for this species in West Hungary, and we also found that the temperature of the 60 days preceding flowering (Mar-Apr, T216) is strongly related to the timing its flowering. A similar relationship has already been demonstrated between the emergence of *C. majalis* shoots and the Feb-Apr temperature by Sparks *et al.* (2011) in western Poland. Furthermore, we have also found a weak but noteworthy memory effect: several temperature and NAO variables from the previous autumn (T108, T111, T310, N309) seemed to influence the beginning of flowering of this species. Such impact of the previous autumn's weather has already been documented for other herbaceous species (Crimmins *et al.*, 2010). At semi-arid environments, autumn conditions are more important to low-elevation species and spring variables found to play greater role in flowering of high-elevation species (Crimmins *et al.*, 2010).

One of the most explored species in Hungary in terms of shifts in flowering phenology is *Robinia pseudoacacia.* Using a long-term data series of 144 years (1851–1994) Walkovszky (1998) showed 3–8 days advancement in the flowering date of *R. pseudoacacia*, relating the event to the mean temperature of March-May. Our results confirm the findings of temperature sensitivity of this species (with an effective period of (Mar-)Apr-May, T216 & T315), but we did not find any significant shifts in flowering during our study period (1952-2000). At the European level the flowering of *R. pseudoacacia* shows stronger response to temperature in colder countries (Menzel *et al.*, 2006). In contrast to the response of other species (Menzel *et al.*, 2006), *R. pseudoacacia* has negative regression coefficients of the temperature sensitivity against flowering. In Poland, Jatczak and Walawender (2009) has found an advancement of 2.7 days per decade for this species during the second half of the 20th century.

Sambucus nigra flowering in Europe is shifting in average ˜2.8 days earlier per decade (Menzel, 2000). There is also clear documented temperature sensitivity for this species: Sparks *et al.* (2000) have found a strong relationship with March and April mean temperatures. This influence of the spring temperatures are clearly supported also with our results showing an unambiguous and highly significant negative relationship between the timing of flowering and the trimonthly temperature of the current year's Mar-May period (T315). And additionally, we also documented a relatively clear influence of NAO for almost the same period (N216) in the only macroregion lacking a significant temporal trend (r5).

Late spring temperature values (Apr-Jun: T117, T216, T316) were the most influential ones also in case of *Tilia cordata*, but we also documented a relatively clear long term influence of previous year's early spring temperature and precipitation as well (Feb-Apr: T302, P302). Schleip *et al.* (2009) have also found that April-June temperatures influence the flowering of the closely related *Tilia platy-*

phyllos, even though the strength of this relationship (temperature weights) was weaker than for most of the other studied tree species.

The connections between flowering phenologies and climate identified in this paper offer some insight into the future potential consequences of climate change in this region. As the temperature increase expected in Hungary (Krüzselyi *et al.*, 2011) may considerably exceed the global rate of warming (Bartholy *et al.*, 2009b; Pieczka *et al.*, 2010), future advancement of spring flowering is to be expected. Further understanding of the relationship between plant phenologies and climate in Central and Eastern Europe may be gained from future studies on more species and phenophases. There is still a lot of data to analyze in Hungary, as well as in other European countries (Szabó *et al.*, 2014). For detecting climate change impacts the best solution would be a coordinated renaissance of the national phenological observation networks in this region, supported by citizen science.

CHAPTER 3

Phenological patterns of flowering across biogeographical regions of Europe*

Abstract

Long-term changes of plant phenological phases determined by complex interactions of environmental factors are in the focus of recent climate impact research. There is a lack of studies on the comparison of biogeographical regions in Europe in terms of plant responses to climate. We examined the flowering phenology of plant species to identify the spatio-temporal patterns in their responses to environmental variables over the period 1970–2010. Data were collected from twelve countries along a 3000 km long, North–South transect from northern to eastern Central Europe. Biogeographical regions of Europe were covered from Finland to Macedonia. Robust statistical methods were used to determine the most influential factors

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*The manuscript (Templ *et al.*, 2017) was accepted (19.01.2017) for publication in *International Journal of Biometeorology*, DOI: 10.1007/s00484-017-1312-6.

driving the changes of the beginning of flowering dates. Significant species-specific advancements in plant flowering onsets within the Continental (3 to 8.3 days), Alpine (2 to 3.8 days) and by highest magnitude at the Boreal biogeographical regions (2.2 to 9.6 days per decades) were found, while less pronounced responses were detected at the Pannonian and Mediterranean regions. While most of the other studies only use mean temperature in the models, we show that also the distribution of minimum and maximum temperatures are reasonable to consider as explanatory variable.

Not just local (e.g. temperature) but large scale (e.g. North Atlantic Oscillation) climate factors, as well as altitude and latitude play significant role in the timing of flowering across biogeographical regions of Europe. Our analysis gave evidences that species show a delay in the timing of flowering with an increase in latitude (between the geographical coordinates of 40.9-67.9), and an advance with changing climate. The woody species (*R. pseudoacacia* and *T. cordata*) showed stronger advancements in their timing of flowering than the herbaceous species (*T. officinale*, *C. majalis*). In later decades (1991–2010) more pronounced phenological change was detected than during the earlier years (1970–1990), which indicates the increased influence of human induced higher spring temperatures in the late 20th century.

3.1 Introduction

The scientific understanding of the causes of observed changes in the climate system has been increasing according to the report of the Intergovernmental Panel on Climate Change (Stocker *et al.*, 2013). Climate model projections indicate that, regarding temperature and precipitation changes, similar tendencies are likely to continue over the coming century; however, future changes will vary across regions

(Stocker *et al.*, 2013). These evidences also call ecologists‘ attention to phenomena in the natural ecosystems‘s shifting in time related to global warming (Walther *et al.*, 2002; Parmesan, 2006; Parry *et al.*, 2007; Franks, 2015).

Phenology is the study of periodically repeating stages in the life cycle of animals and plants as influenced by environmental conditions (Demarée and Rutishauser, 2009). The likelihood of species occurrence in a certain area depends on survival and reproduction, which are both depending on the species' phenology and thus intimately linked to climate (Cleland *et al.*, 2007). Observational (Menzel *et al.*, 2006; Koch *et al.*, 2009b; Schleip *et al.*, 2009), field experimental (Wolkovich *et al.*, 2012), predicted (Aguilera *et al.*, 2015) and remotely sensed (White *et al.*, 2005) data suggest that the timing of several plant phenological phases advance and / or delay across the globe, from the Northern (Schwartz *et al.*, 2006) to the Southern Hemisphere (Chambers *et al.*, 2013) due to climatic changes. Several studies demonstrate significant advancements in phenological phases of plants across Europe (Menzel and Fabian, 1999; Chmielewski and Rotzer, 2001; Schleip *et al.*, 2009). These changes in central Eastern Europe have so far been documented to be less marked than in western and central Europe (Askeyev *et al.*, 2010).

Climate factors, phenophases and their timing play the most important role in such changes. The main causes depend on the climatic region(s) from Mediterranean to high latitudes. The most influential variables are temperature (Rutishauser *et al.*, 2009), precipitation (Penuelas *et al.*, 2004), photoperiod (Körner and Basler, 2010), the North Atlantic Oscillation (Scheifinger *et al.*, 2002), as well as cold or warm spells (Menzel *et al.*, 2011) and edaphic factors (Wielgolaski, 2001).

Biogeographical regions are useful geographical reference units when describing habitat types and species living under similar conditions in different countries (Roekaerts, 2002). The establishment of plant phenology across regions of Europe is a first important step towards providing a general overview, still covering a wide spatial window. The purpose of the study presented in this Chapter was (i) to compare different biogeographical regions (Boreal, Continental, Alpine, Pannonian and Mediterranean), and test whether the areas experienced any trends in flowering time, (ii) to evaluate the possible factors that influence phenological shifts, and (iii) to discover phenological patterns along various latitudes and periods (1970–1980, 1981–1990, 1991–2000 vs 2001–2010).

3.2 Materials and methods

Phenological data of plants

Phenological data we analysed were collected from twelve countries (Finland, Estonia, Latvia, Lithuania, Poland, Slovakia, Hungary, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Macedonia) in northern to eastern Central Europe for the period 1970–2010 (Figure 3.1). The data comprise phenological records on the beginning of flowering time of six plant species: lily of the valley (*Convallaria majalis* L.), common dandelion (*Taraxacum officinale* L.), common lilac (*Syringa vulgaris* L.), black elder (*Sambucus nigra* L.), black locust (*Robinia pseudoacaica* L.), and small-leaved lime (*Tilia cordata* Mill.). Even though the datasets include observations originating from different phenological networks (Table 3.1), the studied beginning of flowering (BF) event was consequently defined as ”the appearance of the first flowers producing pollen on at least 10 % of the observed plants visible”. This phenophase equals the event 61, according to the BBCH (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry) code (see Meier, 2001). The observations provided coverage for twelve North- and East-Central European countries along the geographical coordinates of 40.9°–67.9°latitudes ranging to the 13.6°–32.1°longitudes (Figure 3.1). The aim of the phenological site selection was to provide the best temporal and spatial coverage as possible. To reach this, the selection criteria were as follows: (1) the site has at least 10 years of continuous records; (2) there are at least 5 sites within one biogeographical region. This criteria set resulted in the North–South phenological (NS-Pheno) database (see also Templ *et al.*, 2016) that included different numbers of observations per biogeographical region.

The indicative map of European Biogeographical Regions was first defined in practice of the conservation of natural habitats, wild fauna and flora (Roekaerts, 2002; ETCBD, 2006). The dataset of biogeographical regions was taken from the European Environment Agency web page[†]. We merged these data sets with the phenological time series in order to compare the following biogeographical macroregions: Boreal, Continental, Alpine, Pannonian and Mediterranean (Figure 3.1).

The Boreal region is the largest biogeographical region of Europe. Its climate is cool and mainly continental, its vegetation is dominated by coniferous forests, while the biodiversity is relatively low. The Continental region is characterized by clear continental climate, especially across the central and eastern parts. Widespread grasslands are decreasing due to intensification of agriculture and afforestation. The region shows increasing fragmentation of habitats due to dense and increasing infrastructure within urban areas. The Alpine region is determined by vertical zonality induced by the exposition of mountain slopes and advecting air masses. In this way, different ecological conditions are represented at different altitudes resulting in various vegetation types. The Pannonian region, situated in the lowland areas of the Carpathian Basin used to be dominated by a mosaic of deciduous forests and forest steppes, which are mostly turned into agricultural fields by now. The Mediterranean region is characterized by a climate where warm, moist winters alternate with hot, dry summers. The region is dominated by evergreen forests and shrublands.

[†] http://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-1

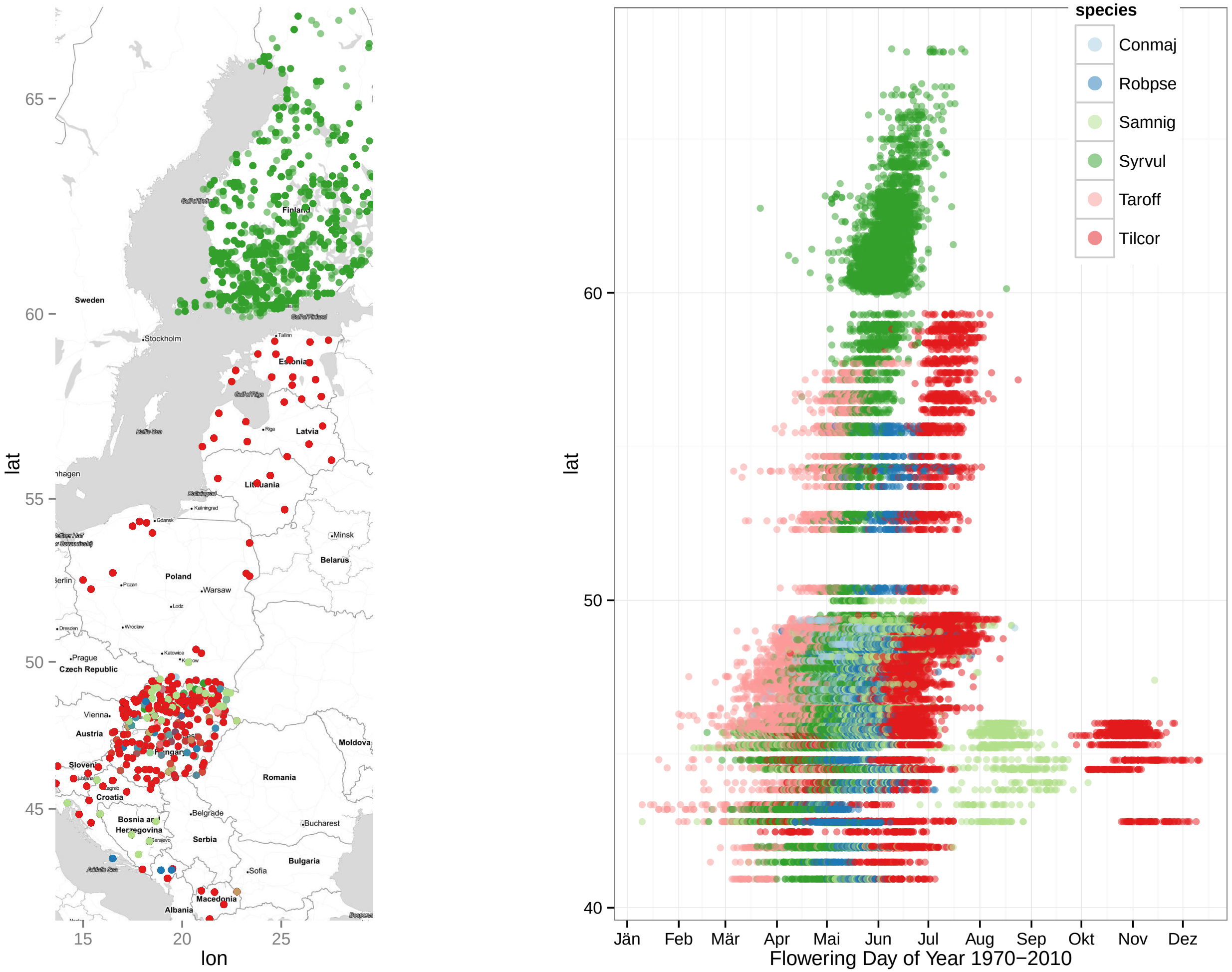

Figure 3.1: Left panel: Locations (dots) of the 963 phenological stations in certain biogeographical regions of Europe along a North–South transect where phenological records have been collected. Right panel: Flowering time (1970–2010) of the studied species shows the relation to latitude. (The colour key of both panel correspond to the plant species: (i) Conmaj (*C. majalis*) – light blue, (ii) Robpse (*R. pseudoacacia*) – blue, (iii) Samnig (*S. nigra*) – light green, (iv) Syrvul (*S. vulgaris*) – green, (v) Taroff (*T. officinale*) – light red, (v) Tilcor (*T. cordata*) – red.)

Table 3.1: Phenological networks along a North to South transect in Europe, maintaining observations and provided data by the members of the NS-Pheno Team

Country	Observational network	Reference
Finland	National Phenological Network	Kubin *et al.* (2007)
Estonia	Estonian Naturalists Society, Estonian Environment Agency	Ahas and Aasa (2006)
Latvia	volunteer collected sites	Grisule and Briede (2008)
Lithuania	Voke Branch of the Lithuanian Research Centre for Agriculture and Forestry	Romanovskaja and Baksiene (2008)
Poland	Institute of Meteorology and Water Management	Niedžwiedž and Jatczak (2008)
Slovakia	Slovak Hydrometeorological Institute	Remisová and Nejedlik (2008)
Hungary	Hungarian Meteorological Service	Szalai *et al.* (2008)
Slovenia	Environmental Agency of the Republic of Slovenia	Crepinsek *et al.* (2008)
Croatia	Meteorological and Hydrological Service	Vučetić *et al.* (2008)
Bosnia and Hercegovina	National Phenological Network	Hodžič and Voljevica (2008)
Montenegro	National Phenological Network	Popovič and Drljevic (2008)
Macedonia	National Phenological Network	Nekovár *et al.* (2008)

Environmental data

Climatic variables based on air temperature (daily arithmetic mean, minimum, maximum), precipitation and the indices of the North Atlantic Oscillation (NAO) were obtained from different databases. Daily data (January to May) of air temperature and precipitation were used from the E-OBS high-resolution gridded dataset developed by the ENSEMBLES EU-FP6 project[‡] with a 0.25 degree spatial resolution (Haylock *et al.*, 2008).

As a descriptor of the frequency distribution, the quartiles at 0.25 (*Q.25*), 0.5 (median), 0.75 (*Q.75*) level and the skewness of climate data series were determined. Additionally to raw climate data, the motivation behind using such characteristics of predictors was to also take into account the spread of values, in terms of the interquartile distance. This is often done using the classical standard deviation. However, since squared distances to the mean are taken into account, outliers have a large influence on this estimate.

We created a set of environmental predictors (a) for monthly temperature (namely, the 0.25, 0.5, 0.75 quartiles and skewness of the minimum-, mean-, maximum- temperature datasets) and (b) for precipitation (0.25, 0.5, 0.75 quartiles and skewness of the monthly precipitation).

Additionally, monthly indices (January to May) of the NAO (Hurrel, 1995) were used from the database provided by the Climatic Research Unit (CRU) of the University of East Anglia.

Furthermore, metadata information regarding the locations, namely latitude, longitude and altitude of phenological sites, were also used in the models to consider spatial differences.

[‡] http://www.ecad.eu/download/ensembles/ensembles.php

Data analysis

Data pre-processing: Dates of the phenological observations –flowering data– were converted to days of the year (doy), starting with first of January and considering leap years. Each phenological station (shown in Figure 3.1) was assigned to the closest grid cell.

Calculation of trends: The obtained time series were assigned to 5 biogeographical regions (Figure 3.1), based on the code list of the European Environmental Agency. Accordingly, trend analyses were carried out on long-term (1970–2010) data series of (a) monthly climate data (Figure 3.2) and (b) flowering onset (Figure 3.3) for each biogeographical region. We found that the data contain outliers, therefore a robust regression method, namely MM-type estimators for linear regression (see Maronna *et al.*, 2006) were applied to calculate trends. The reason for using this method was that least squares estimates for regression models are highly sensitive to outliers. Outliers are observations which do not follow the pattern of the other observations. Robust techniques reduce the influence of outliers (without removing them from the data series), but approximately give the same results as if no outliers were presented in the dataset (see more details in Todorov and Filzmoser, 2009). Finally, significant trends were found at the level of significance $p < 0.05$ using the Mann-Kendall trend test (Mann, 1945).

Comparison of decades: In order to compare various decades, phenological time series were divided into four decadal-long periods: 1970–1980, 1981–1990, 1991–2000 and 2001–2010. As it was found to be a highly influential factor, the differences in flowering onset dates (station-wise) according to latitudes (N) were analysed. Trends in the timing of flowering dates were illustrated with regression lines using locally weighted scatterplot smoothing (loess) (Cleveland, 1979) for all decades (Figure 3.4).

Influence of environmental variables: To describe the influence of the environmental variables on the timing of flowering, we again used robust MM-type estimators for linear regression (see Maronna *et al.*, 2006) on each plant species for each biogeographical region. The difference between the models was only given by the applied explanatory variables. Namely, the climatological data sets preceding the timing of flowering and metadata information about the station locations were included in the models, fitted by the *lmrob* function of the R package robustbase (Rousseeuw *et al.*, 2015). For better interpretability, the predictors were standardized to zero mean and unit variance. The predictor expressing the first quartile of precipitation was excluded from the models because these first quartiles were mostly zero. The estimated regression coefficients obtained with robust methods were visualized on heatmaps (Figure 3.5). On the heatmaps we distinguish between cells including values of corresponding regression coefficients and empty (white or grey) cells. The color key of the heatmaps expresses the values of the regression coefficients. Namely, the darker the color the stronger the effect, which is either negative or positive. Naturally, the maximum and minimum of the coefficients vary depending on each heatmap. For better comparison, the colour range was restricted to -1 and 1, thus any coefficient larger or smaller than this range was assigned to black colour. Non-significant regression coefficients were suppressed to reduce the amount of information to gain a better overview about the important values. Thus, for any empty white-coloured cell the null hypothesis (regression coefficient equals zero) cannot be rejected (no effect). The empty grey-coloured cells report that no data were available in some biogeographical regions for certain species.

All statistical analyses were performed using R (R Development Core Team, 2015, version 3.2.2).

3.3 Results

Trends in climatic variables

Regarding the climatological variables, we found that the monthly mean (Figure 3.2), minimum, maximum temperatures preceding the flowering onset dates showed significant warming trends (1970–2010) across the Alpine and continental regions calculated by the Mann-Kendall trend test. Temperature has been increased significantly during April (1970–2010) across the Mediterranean and the Pannonian region. Over the studied 41 years, the Boreal region did not show significant changes in temperature. Furthermore, we did not detect any significant long-term changes in case of precipitation and NAO.

Temporal characteristics of flowering

According to climatological trends, this section provides an overview about flowering trends (1970–2010) over biogeographical regions of Europe, with special interest on the North–South transect, drawn by latitude. As expected, the flowering time starts earlier across the warmer Mediterranean and Pannonian regions, i.e. along the lower latitudes, while it starts later across the cooler Boreal and Alpine regions. From 23 studied cases, 17 showed significant flowering trends (Figure 3.3). All of these phenological changes were related to earlier appearance – indicated by negative regression coefficients (Table 3.2). Most species showed significant trends in the Continental and Alpine regions (Table 3.2), according to significant temperature increase (Figure 3.2). Less significant phenological shifts were found across the Pannonian region. However, data availability does not allow us to give such general statements about phenological changes in the Mediterranean region. Still it is noticeable that all coefficients were negative (except for *S. vulgaris* in the Boreal region and *C. majalis* in the Pannonian region) indicating advance-

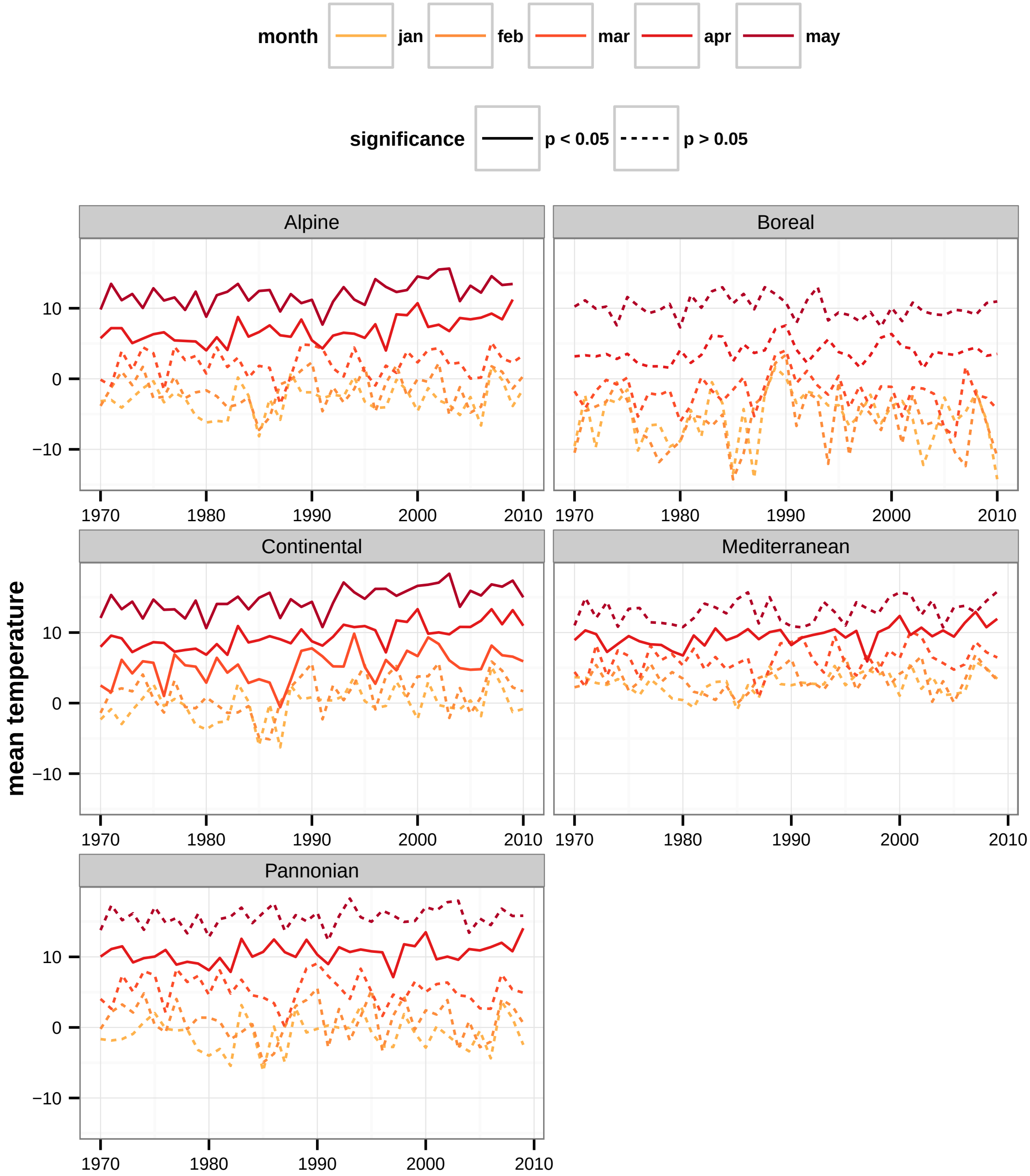

Figure 3.2: Annual variation and trends (1970–2010) of monthly mean temperature (°C) in different biogeographical regions of Europe. Solid lines report significant trends.

ments in flowering time (Table 3.2). The strongest advancement was found for *R. pseudoacacia* (3.8–9.6 days earlier shift per decade) and *T. cordata* (3.2-9.5 days per decade), while less pronounced responses were given by the herbaceous *T. officinale* and *C. majalis* (Table 3.2).

Figure 3.3: Inter-annual variation in the timing of flowering (doy) in different biogeographical regions of Europe (1970–2010). Solid lines report significant trends.

Furthermore, we detected differences in the mean flowering onset date between decades (Figure 3.4). Differences were detected in mean flowering date (doy) along a North–South transect as we evaluated the time series over different time peri-

Table 3.2: Coefficients of robust linear regression between flowering onset and years (1970–2010) for the studied species and biogeographical regions in Europe. Negative values: indicate advancement in the beginning of flowering. Significant relationships ($p < 0.05$) are visualized in bold.

species	Alpine	Boreal	Cont.	Mediter.	Pannonian
Convallaria majalis	**-0.20**				0.07
Robinia pseudoacacia	**-0.38**	**-0.96**	**-0.69**	**-0.17**	**-0.18**
Sambucus nigra	**-0.35**		-0.30		**-0.18**
Syringa vulgaris	**-0.39**	0.03	**-0.55**	**-0.24**	-0.08
Taraxacum officinale	-0.16	**-0.22**	**-0.83**		-0.16
Tilia cordata	**-0.32**	**-0.95**	**-0.52**		-0.01

ods. Accordingly, the flowering of different species generally starts earlier in the latest period (1991–2010) compared to the earlier years (1970–1990). This applies especially to *R. pseudoacacia, S. vulgaris* and *S. nigra* over the whole range of latitudes. For other species, like *T. officinale*, this is only true along some ranges of latitudes, especially in the southern part of Northern Europe. However, because of missing data problems (no values for the North during the period 2001–2010) not much can be concluded from the current database for *T. cordata*.

Spatial patterns in flowering phenology across Europe

In order to explain the causes of phenological changes, the effect of climatic variables and geographical information on flowering dates were analysed (1970–2010). In Figure 3.5 we illustrate the robust regression coefficients for the six species in each biogeographical region of Europe using heatmaps. In most cases, the effects of latitude and altitude were significantly positive. Thus, the species living in northern or higher habitats were characterized by later dates of flowering onset (see Figure 3.4).

On the contrary, the effect of longitude was rather negative or non-explainable

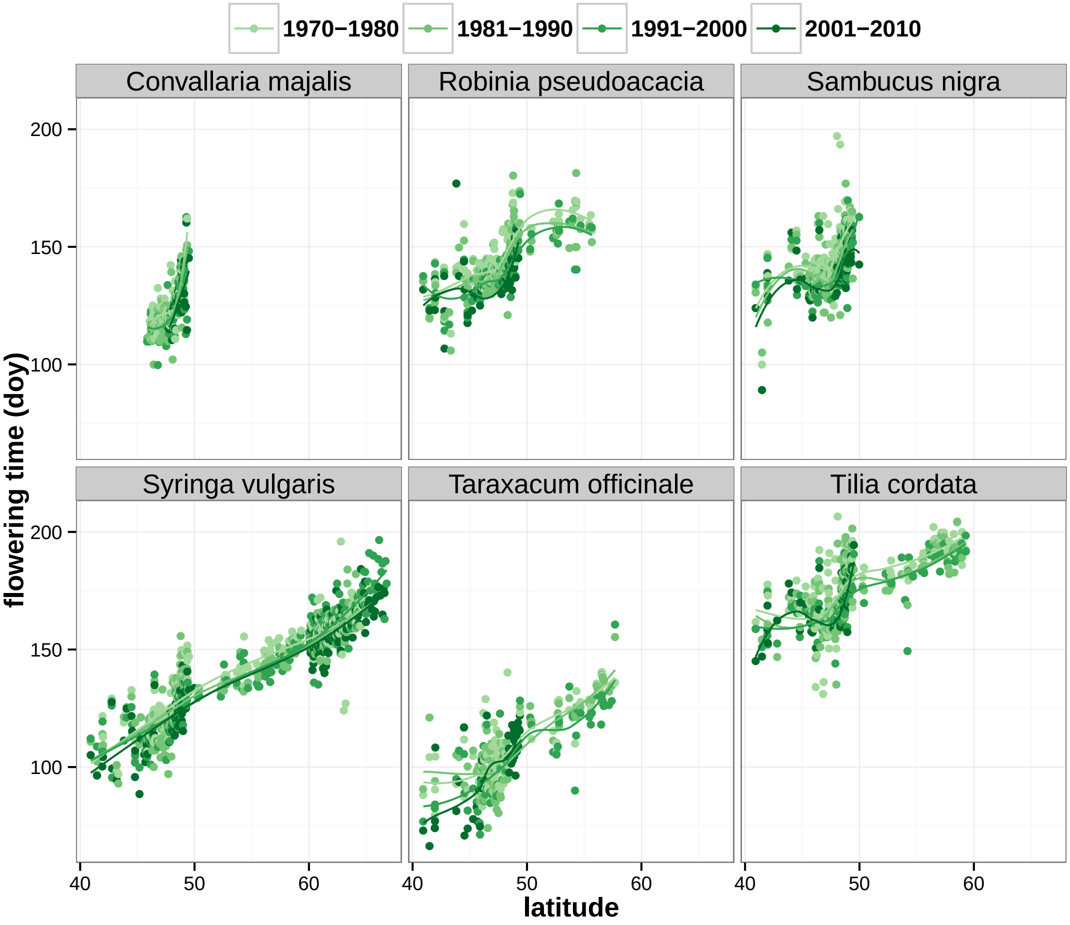

Figure 3.4: Flowering onset dates (station-wise) against latitude over different decades (1970–1980, 1981–1990, 1991–2000, 2001–2010) and corresponding regression lines (loess).

(70 % of the cases). This indicates that the species living in more eastern parts of Europe were characterised by earlier dates of flowering.

Regarding climatological variables, the clearest pattern arises from the indirect effect of NAO. All species revealed a significantly negative relationship to the index of NAO (Figure 3.5).From our study, the effect of mean temperature seems to give the most vague information. Earlier flowering in response to increased temperatures is better visible when looking at the minimum and maximum temperatures and thus it is easier to interpret the flowering dates with the distribution of minimum and maximum temperatures. It can be seen that in most cases, the quartiles of the minimum temperature have negative effect on the timing of flowering. Namely, the higher the minimum temperature the earlier the flowering time – except in the Alpine region. The second (median) and third quartiles of the maximum temperature distribution also show negative effects (again except for the Alpine region). The effect of precipitation did not show a general pattern among species and biogeographical regions, but about half of the the studied cases indicated significant influence.

3.4 Discussion

The term of *phenological pattern* has mainly been associated with plant communities (e.g. Pilar and Gabriel, 1998; Martinková *et al.*, 2002)); in other cases, areas at different scales were compared to describe phenological patterns of areas. Studies have described phenological changes in timing of various spring plant phenophases across hemispheres (Schwartz *et al.*, 2006; Chambers *et al.*, 2013), continents (Menzel and Fabian, 1999), along countries (Ahas and Aasa, 2006; Kalváne *et al.*, 2009; Szabó *et al.*, 2016) and zones (Karyieva *et al.*, 2012) related to climate driven mechanisms and recent human induced climatic changes. Phenological events of

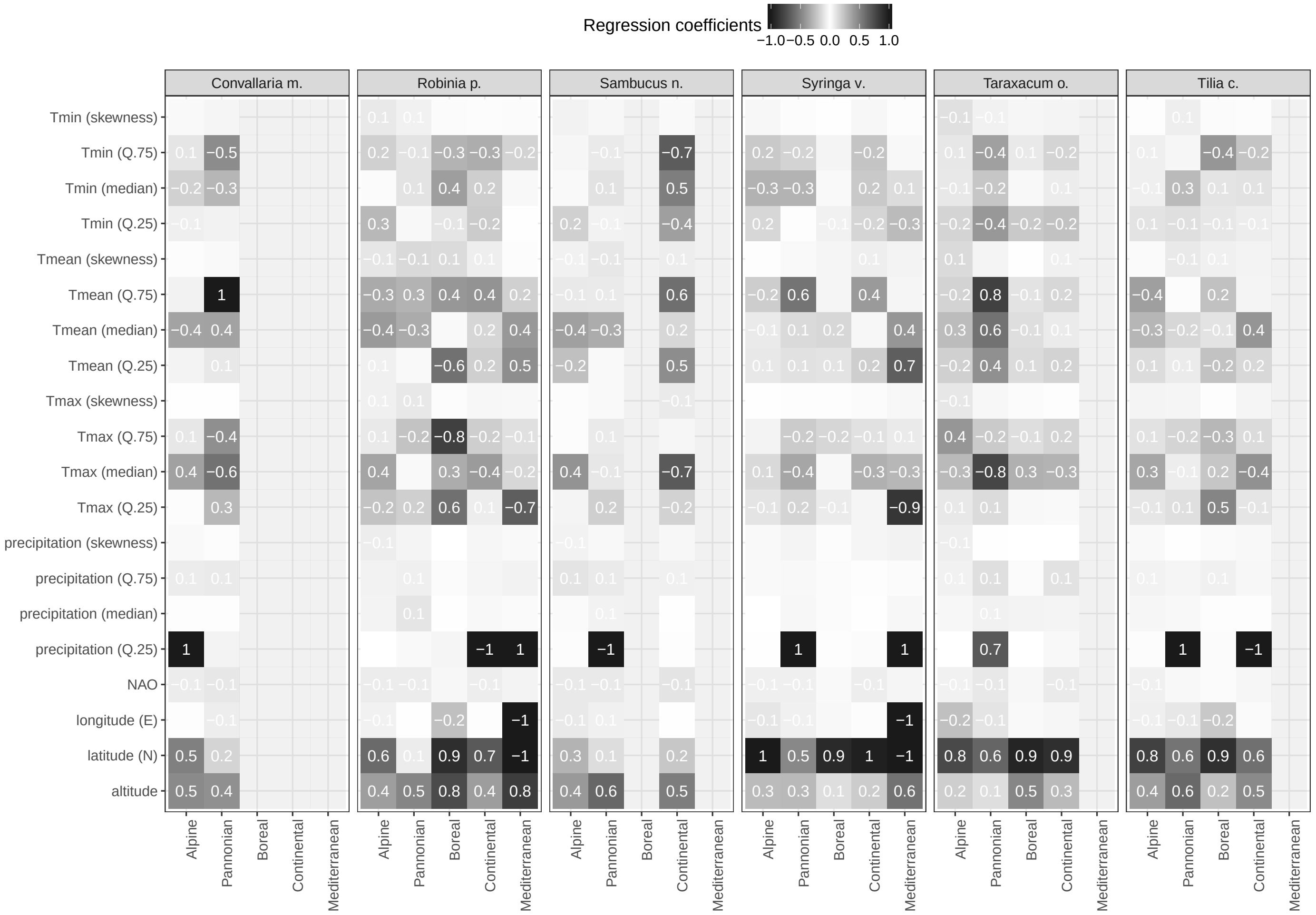

Figure 3.5: Regression coefficients given for each plant and explanatory variable within different biogeographical regions of Europe. Cases of grey cells without values report that no data were available in those biogeographical regions. White cells indicate that non-significant influence was found. Negative values indicate negative influence on flowering time (i.e. advancement), while positive values express positive effect.

plants across biogeographical regions are particularly poorly documented, except the efforts done by Rodriguez-Galiano *et al.* (2015) and Templ *et al.* (2016).

We aimed to discover phenological patterns across biogeographical regions of Europe between various time windows of the period 1970–2010. Besides the established NS-Pheno database, the novelty in our study is that we described flowering patterns along a 3000 km long North–South transect of Europe. Our NS-Pheno database allowed us to test, if the species living in the northern latitudes show more pronounced response to climate change than those living in southern biogeographical regions. In the Boreal region, the intensity of the phenological response of *Betula pubescens* to temperature increases from South to North across Finland (Pudas *et al.*, 2008). The reason is that the observed (1847–2013) warming in Finland is almost twice as high as the global temperature increase (Mikkonen *et al.*, 2015). Our results seem to be contradictory to the findings of Mikkonen *et al.* (2015), because we did not show significant temperature increase in this region (Figure 3.2). But in contrast to Mikkonen *et al.* (2015), we studied shorter time series (1970–2010) and applied robust methods, which both may have influence on the results. Similarly to Lappalainen *et al.* (2008), we experienced the most pronounced advancing flowering trends (Table 3.1) at a species level within this subarctic climate zone. There is also a known phenological sensitivity of species in other boreal countries such as in Estonia (Ahas and Aasa, 2006), Latvia and Lithuania (Kalvâne *et al.*, 2009). Furthermore, our results confirm the observed climate variability patterns and trends in the Alpine region (Auer *et al.*, 2007; Gobiet *et al.*, 2014). Namely, the region has been facing a significant temperature increase (Figure 3.2), which resulted in significant phenological shifts in the area (see Table 3.2). As we move from the northern areas to temperate and cool climate zones, phenological responses of plants to warmer environment are strong (Menzel *et al.*, 2006; Jatczak and Walawender, 2009). The territory of Hungary covers 80–85 % of the drier Pannonian region. For this region Szabó *et al.* (2016) already showed that plant species advanced their flowering time (1952–2000) by 1.9-4.4 days per decade. This tendency is confirmed in our study, but only for 2 out of 5 species significantly (Table 3.2), which inconsistency might stem from the different i) lengths of the study periods and the ii) number of stations per region involved in the analysis.

It is known that the annual pattern of phenological seasons across Europe is related to the North Atlantic Oscillation (Menzel *et al.*, 2005). Similarly to most of the studies, we have also found temperature to be an influential determinant for the timing of flowering (Stocker *et al.*, 2013). Our results highlighted that not just the mean temperature but the distribution of minimum and maximum temperatures are reasonable to consider as explanatory variables when explaining flowering times. The importance of rainfall and water availability is pronounced by Penuelas *et al.* (2004) as complex drivers of phenological shifts. We showed (Figure 3.5) a significant influence of precipitation on the beginning of flowering in approximately half of the studied cases.

Our main focus was not only to test the effect of climatic variables, but also others such as latitude. We addressed the question: Which patterns can we draw when comparing northern biogeographical regions to southern ones? Are they similiar to the patterns shown for the territory of China (Ge *et al.*, 2015) and the findings of a meta-analysis conducted by Root *et al.* (2003)?

It is known that over the past half century the temperature along higher latitudes has increased more than along lower latitudes (Stocker *et al.*, 2013). Accordingly, Root *et al.* (2003) showed that the estimated phenological shifts from 32.0°N to 49.9°N latitude are smaller than between the 50.0°N to 72.0°N latitude band. Our observations confirm these findings for Europe, since we noticed the most significant plant responses within the Boreal biogeographical region (approximately between 54.0°N and 67.0°N), which was followed by the Continental and Alpine regions (from 40.0°N in 55.0°N). But, is only the latitude responsible for this pattern? Ge *et al.* (2015) investigated the 20.0°–50.0°latitudes in China and found significant phenological advancements, however, they could only explain 9 % of the overall variance in spring phenological trends. Previously, Estrella *et al.* (2009) stated that the geographic coordinates (latitude and longitude) have only a modest influence on the mean onset of the groups of phenophases, however, inclusion of altitude can improve models for some cases. In our study, not only the effects of latitude (Figure 3.4), but also altitude were found to have a significantly positive effect on the beginning of flowering (Figure 3.5). These findings indicate that although we experience a similar pattern (stronger response at higher latitudes) among continents, the drivers of these changes cannot be described simply. We showed that among biogeographical regions of Europe, the effect of longitude was mostly non-significant. This can be explained by the longitudinal extent of our study window, which probably was too narrow (13.6°–32.1°longitudes) to show any West–East oriented flowering pattern. Therefore our results cannot support the findings of Askeyev *et al.* (2010) who demonstrated less marked phenological changes at the eastern edge of Europe.

According to our results, more pronounced phenological changes occur in the latest (1991–2010) than in the earliest (1970–1990) study periods, as the effect of climate change is more and more influential since the industrial era (Stocker *et al.*, 2013).

CHAPTER 4

Change of plant phenophases explained by survival modelling*

Abstract

It is known from many studies that plant species show a delay in the timing of flowering events with an increase in latitude and altitude, and an advance with an increase in temperature. Furthermore, in many locations and for many species, flowering dates have advanced over the long-term. New insights using survival modelling are given based on data collected (1970–2010) along a 3000 km long transect from northern to eastern Central Europe. We could clearly observe that in the case of common dandelion (*Taraxacum officinale*) the risk of flowering time, in other words the probability that flowering occurs, is higher for an earlier day of year in later decades. Our approach assume that temperature has greater influence than precipitation on the timing of flowering. Evaluation of the predictive power of tested models suggests that Cox models may be used in plant phenological

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*The related paper is co-authored with Stefan Fleck and Matthias Templ (Templ *et al.*, 2016) and online first published in *International Journal of Biometeorology*, DOI: 10.1007/s00484-016-1267-z.

research. The applied Cox model provides improved predictions of flowering dates compared to traditional regression methods, and gives further insights into drivers of phenological events.

4.1 Introduction

Phenology is the study of the seasonal timing of recurrent biological events (such as flowering, migration of birds and emergence of insects), the causes of their timing with regard to biotic and abiotic forces, and the interrelations among phenophases (developmental stage) of the same or different species. Drivers of phenological responses range from macroclimatic circulation patterns (e.g. North Atlantic Oscillation) (Stenseth *et al.*, 2003), to local environmental factors such as photoperiod (Körner and Basler, 2010), edaphic factors (Wielgolaski, 2001), precipitation (Fu *et al.*, 2014) and temperature (Parry *et al.*, 2007). Several studies have demonstrated significant changes in plant phenological events in the Northen and Southern Hemisphere (Menzel *et al.*, 2006; Schwartz *et al.*, 2006; Way, 2011; Chambers *et al.*, 2013). However there are variations in the trends of phenological time-series caused by phenophases, species, study periods and geographical locations. Thus differing responses to climate change can result in mismatches between the timing of plant and insect life cycles that impact other trophic levels, and which may lead to population declines (Walther *et al.*, 2002).

The phenology of most plant and insect species depends strongly on the thermal accumulation, determined by daily temperature. Each phenophase of an organism has its own total heat requirement and there have been many attempts to predict the onset of plant phenophases using heat sums. Most of these studies were conducted on agricultural species, e.g. budburst date in vineyards (Cortazar-Atauri *et al.*, 2009), maturation in apricot cultivars (Ruml *et al.*, 2011) or pollen prediction (Garcia-Mozo *et al.*, 2009), where accurate forecasts are crucial.

Various methods have been tested previously to model the relevance of environmental conditions for plant phenophases. Current plant phenological studies either focus on temporal and spatial characterization of a stage in the annual life cycle of a plant based on observed or modeled data, or attempt to predict the future timing of plant stages. Survival analysis is a branch of statistics (see e.g. Rodriguez, 2007) which deals with the analysis of the time duration until one or more events happen. Proportional hazard models — such as the one proposed by Cox (1972) — were originally developed for the medical field. In our case, the event of interest is the flowering time of a plant species rather than patient survival time. Such models are nowadays applied to a broad range of "time to event" data sets in ecological studies as well (Kleinbaum and Klein, 2012). Examples range from improved understanding of spring migration phenology (Bauer *et al.*, 2004), estimation of population growth predictions for an endangered species (DeCesare *et al.*, 2014), as well as the development of a descriptive model for egg-laying dates of birds Gienapp *et al.* (2005, 2010).

We attempt to improve our understanding of flowering time by applying a non-traditional method, proportional hazard models to plant phenology. We used common dandelion (*Taraxacum officinale* W.) as a model organism, because accurate long-term (1970–2010) data sets from biogeographical regions of Europe are available for this species. By calculating the hazard ratio of different climate variables, we showed their influence on flowering times and tested the predictive power of Cox models in phenological research.

4.2 Materials and methods

Phenological data

Plant phenological time-series were collected for the period of 1970–2010 from northern to eastern Central Europe. These data comprise phenological observations of common dandelion (*Taraxacum officinale L.*, Asteraceae).

The studied beginning of flowering (BF) event was defined as "the appearance of the first flowers producing pollen on at least 10 percent of the observed plants visible". This phenophase corresponds to event 61 according to the BBCH (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry) code (Meier, 2001). Data from nine European countries (Finland, Latvia, Lithuania, Poland, Hungary, Slovenia, Croatia, Bosnia and Herzegovina, Macedonia), between 40.9–67.9 degrees in latitude and 13.6–32.1 degrees in longitude, were collected (see Figure 4.1). More precisely, data on *T.officinale* were taken from the NS-Pheno database (Templ *et al.*, 2017) – this is the reason why Figure 4.1 has similarities with Figure 3.1. The NS-Pheno database includes phenological data collected from countries along the North–South transect across Europe (see Table 3.1), coordinated by the author.

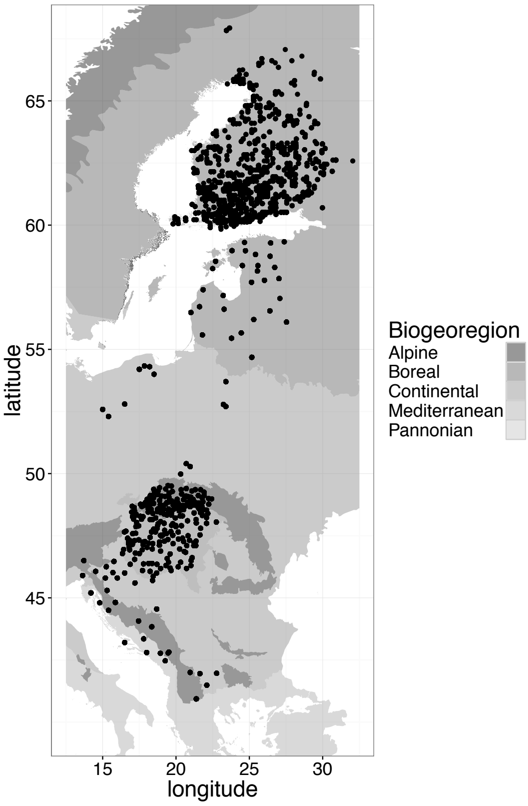

Figure 4.1: Phenological observation sites and the studied North to South transect of biogegraphical regions in Europe.

The database comprises records from the following national observation networks. Phenological data from Finland were recorded by the National Phenological Network (Kubin *et al.*, 2007). Estonia has data over years compiled by the Estonian Naturalists Society and the Estonian Environment Agency (Ahas and Aasa, 2006). Data from Lithuania originate from records collected by the Voke Branch of Lithuanian Research Centre for Agriculture and Forestry (Romanovskaja and Baksiene, 2008). Observations from Latvia (Grisule and Briede, 2008) originate from volunteer-collected sites of the humid continental climatic zones (Kalváne *et al.*, 2009). The Institute of Meteorology and Water Management introduced and provided phenological observations from Poland (Niedžwiedž and Jatczak, 2008). The Slovak Hydrometeorological Institute collected phenological observations from the territory of Slovakia (Remisová and Nejedlik, 2008). The observational network of Hungary (Szalai *et al.*, 2008; Szabó *et al.*, 2016) (the main country of the Pannonian region) was maintained by the Hungarian Meteorological Service. Phenological data preserved by the Environmental Agency of the Republic of Slovenia (Crepinsek *et al.*, 2008) were also included in the database. The phenological network maintained by the Meteorological and Hydrological Service of Croatia (Vučetić *et al.*, 2008) covers all of the main climatic zones (moderate continental, mountain and Mediterranean) of the country. From historical reasons, Montenegro has similar phenological observations (Popovič and Drljevic, 2008) to other former Yugoslavian states. Data were collected from Bosnia and Herzegovina too; however, a number of observational sites were affected by the wars in the 1990s (Hodžič and Voljevica, 2008). The southernmost data provider for this study was Macedonia, which is a mostly unexplored region in terms of phenological research.

Environmental data

Temperature and precipitation data were obtained from the E-OBS regular gridded dataset developed by the ENSEMBLES EU-FP6 project[†] with a 0.25 degree spatial resolution (Haylock *et al.*, 2008; Hofstra *et al.*, 2009). Available temperature data included daily minimum, maximum and mean in degrees Celsius. Precipitation records were available as millimeters per day. The temperature data contained some suspicious observations, where, for instance, the minimum temperature was greater than maximum temperature. To err on the side of caution, such observations were removed from the dataset before further data processing.

The relationship between growing degree days (GDD) and the onset of plant phenophases is well known (Cleland *et al.*, 2007). A degree day is a measure of the amount of heat that accumulates above a specified base temperature during a 24 hour period. Phenological models are usually based on accumulated temperature, termed growing degree days, which were calculated as:

$$GDD = \frac{T_{\text{max}} + T_{\text{min}}}{2} - T_{\text{base}}, \tag{4.1}$$

where T_{base} was chosen as 10°C for GDD calculations. Days with a mean temperature lower than 10°C were set to zero (McMaster and Wilhelm, 1997).

The data were collected in nine European countries representing five biogeographical regions, namely the Alpine, Boreal, Continental, Pannonian and the Mediterranean (Figure 4.1). We included the dataset of these regions from the European Environment Agency web page[‡]. The biogeographical regions were first defined within the field of conservation biology, and are useful geographical reference units for describing habitat types and species which live under similar conditions (Roekaerts, 2002; ETCBD, 2006).

[†] `http://www.ecad.eu/download/ensembles/ensembles.php`

[‡] `http://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-1`

Instead of incorporating the geographical location of the station into the model (latitude, longitude, altitude) we stratified the model per station, i.e. we included the phenological stations in the Cox model as strata (see Sect. 4.2 and Equation 4.2). For the Cox model this means that a separate baseline hazard function is fitted to each station. This way we lose the ability to make statements on the influence of geographic factors on a fine scale, but we minimize the effect of site-specific environmental conditions on our analysis by the influence of GDDs and precipitation on the beginning of flowering time. Because of the large numbers of climate and phenological stations that we have, we can nevertheless interpret the results by biogeoregion. This is also the strategy that yielded the best predictive power of all our attempts.

Data analysis

Dates of the phenological observations were converted to days of the year (doy) with 1st of January as the starting point. We found that the collected national phenological timeseries (see Section 4.2) were different in their length because of missing values. To handle this and to reach the best temporal and spatial coverage possible, the data were filtered based on the following selection criteria: (1) the station has at least 10 years of continuous records; (2) there are at least 5 stations within one biogeographical region. This way we created single homogenized phenological time series for each biogeographical region, using two-way crossed linear mixed models by using the pheno R package (Schaber, 2012). This approach allows the aggregation of time series data in an optimal manner (details can be found in Schaber and Badeck, 2002).

We modelled the influence of climate variables on the timing of flowering onset as a survival analysis problem. We fitted the Cox proportional hazards model (Cox, 1972) with time dependent covariates (hereinafter Cox model), implemented in the

R package survival (Therneau, 2015). The Cox model can be used to calculate a hazard ratio for each time dependent covariate (climate variables). The hazard ratio can be regarded as the relative risk of an event occurring at time t. In other words, the relative risk is the ratio of the probability of an event occurring in the exposed group (influenced by environmental factors) versus a non-exposed group.

For the purpose of comparison we also fitted a Cox proportional hazards model without time dependent covariates and a classical linear regression model. We used fivefold cross-validation to compare the predictive power of the models and reported the mean error (ME) and mean percentage error (MPE), to indicate whether the forecasts were biased.

In our case, GDD and precipitation were included in the Cox model as cumulative time dependent covariates. To study whether the influence of these covariates varies between biogeographical regions, they were included as an interaction term. In addition, the model was stratified by station to account for geographical variations in flowering time. The hazard was thus defined as

$$h_s(t, X) = h_{0s}(t) e^{\beta_1 X_1(t) b + \beta_2 X_2(t) b} \tag{4.2}$$

where $h_s(t, X)$ is the hazard at time t for stratum (=station) s, $h_{0s}(t)$ is the time-dependent baseline hazard function for a given stratum, X contains the covariate vectors X_1 (growing degree days) and $X_2 =$ (precipitation), b is the vector of biogeoregions, β_1 and β_2 the unknown coefficients to be estimated.

One of the principal results of this modeling approach is the hazard ratio — that is in our case the change in risk of flowering time associated with a unit increase of one of our covariates (GDD, precipitation). For example, a hazard ratio of 1.01 indicates a 1.01 times higher risk of flowering at a given day. Thus, the Cox model can further be used to predict a flowering risk for any given day of the year (daily hazard) based on climate data.

We made several attempts to include geographic variables such as longitude, latitude, and altitude into the Cox model; however, we were not able to produce models that yielded satisfying predictions. This is likely due to the fact that those variables are not sufficient to describe local climatic variations between stations well enough to account for variations in flowering. To get around this problem we stratified the model by stations, thus we removed all static, site-specific factors.

All analyses were performed using the statistical software and environment R (R Development Core Team, 2015), the pheno package in version 1.6, the survival package in version 2.38.3. and for visualization we used the R package ggplot2 (Wickham, 2009) in version 2.1.0.

4.3 Results

In order to calculate the risk of flowering time over Europe, we determined the long-term trends (1970–2010) of climate variables, which were included in the fitted models. We found that the monthly mean, minimum, maximum temperatures (previous to the flowering onset dates) showed significant warming trends in the Alpine and continental regions. We did not find significant changes in temperature for the Boreal region from our dataset (but see Mikkonen *et al.* (2015)). We present results from the Cox model, and we describe the shift of flowering dates using Kaplan-Meier curves (Kaplan and Meier, 1958). We also compare results on the prediction of survival dates with a traditional method (linear regression).

Shift of flowering date and Kaplan-Meier curves

An important part of survival analysis is to show the survival of each group of interest. In our case, various time periods were handled as groups (see Figure 4.2). We visualized the shift in onset of flowering by generating Kaplan-Meier survival curves from the phenological data. The Kaplan-Meier estimator is a stepwise estimator for survival probability, which in our case can be interpreted as the probability that *T. officinale* has already or has not yet flowered. Figure 4.2 shows the percentage of individuals that have not yet flowered at a given point in time. In general, we can see that the latter the decade the earlier the flowering date. More precisely, on a given day of year, the percentages of individuals that have not yet flowered is less in the following decade than in the preceding decade. Differences between the last two decades (1990-2000 and 2000-2010) are especially large. The survival curve relating to the time 1970-1980 period is the exception to this trend, since the temperatures in the seventies (mean flowering time 110 and mean temperature (January till August) 9.36 degree Celsius) were higher than in the eighties (mean flowering time 113 and mean temperature (January till August) 9.19 degree Celsius).

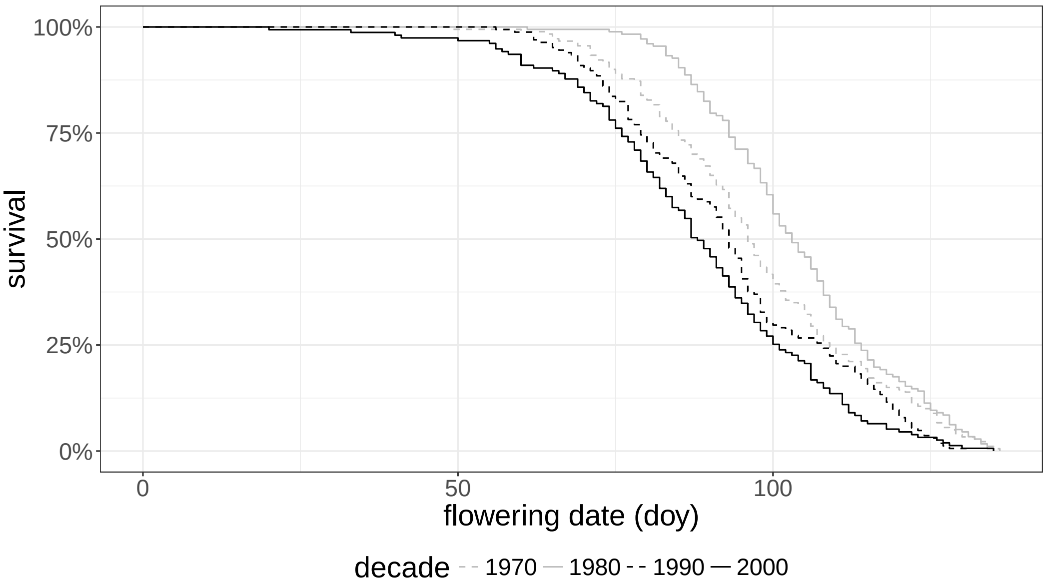

Figure 4.2: Kaplan-Meier survival curves of *Taraxacum officinale* indicating shift in flowering dates over decades.

Table 4.1: Hazard ratios, the change in risk of flowering associated with a unit increase of one of the covariates. Interaction terms between the covariates (growing days degree (GDD), precipitation) and biogeographical regions were also included in the Cox model. Relationships found to be significant ($p < 0.001$) are highlighted in bold. Three statistics were used to evaulate the model fit: Concordance = 0.747 (SE = 0.071), Rsquare = 0.004 (max possible = 0.044), Likelihood ratio test = 830.4 (on 10 df).

Covariates	Hazard ratio	p-value
GDD × Alpine	**1.008**	0.001
GDD × Boreal	**1.016**	0.001
GDD × Continental	**1.012**	0.001
GDD × Mediterranean	**1.011**	0.001
GDD × Pannonian	**1.010**	0.001
Precipitation × Alpine	1.000	0.974
Precipitation × Boreal	1.003	0.035
Precipitation × Continental	0.999	0.327
Precipitation × Mediterranean	1.000	0.870
Precipitation × Pannonian	0.999	0.478

Cox model for time dependent covariates

The hazard ratios and corresponding p-values from the Cox model are reported for each covariate in Table 4.1. The main feature to note in such a table is whether the hazard ratio is greater or smaller than one. As mentioned earlier, a hazard ratio of 1.01 for instance means a 1.01 times higher risk that flowering will happen on any given day per additional growing degree day. A ratio of 1.01 % is thus not a small number since it is a higher risk per day.

Our Cox model found a statistically highly significant link between GDD and onset of flowering time. This relationship varies slightly between different biogeographical regions (see Table 4.1). For precipitation the calculated hazard ratios are ambiguous, because the Cox model found almost no statistically significant link between precipitation and onset of flowering. Only a slightly significant ($p \approx 0.035$) relationship can be shown for the Boreal region, which is likely an artifact because of the large amount of data. The Likelihood ratio (LR) test confirmed that our model was significantly better than the null model (without predictors); the LR test statistic equals 830.4, $p \approx 0$.

We addressed two questions: (i) how do environmental covariates affect the relative risk of the onset of flowering? (ii) is there a significant difference in this risk among the various regions and time periods? The shift of risk of flowering time among decades can be seen in Figure 4.3. The relative risk is a measure relative to the mean covariate (GDD, precipitation and their interaction with biogeographical region) value of each stratum (station). It can be observed that the risk of flowering time is higher for a given date in the year in later decades. Similarities can be seen between decades 1970-1980 and 1980-1990, because of similar temperature conditions. Notice also the similarities between the relative risk and the Kaplan-Meier curves in Figure 4.2.

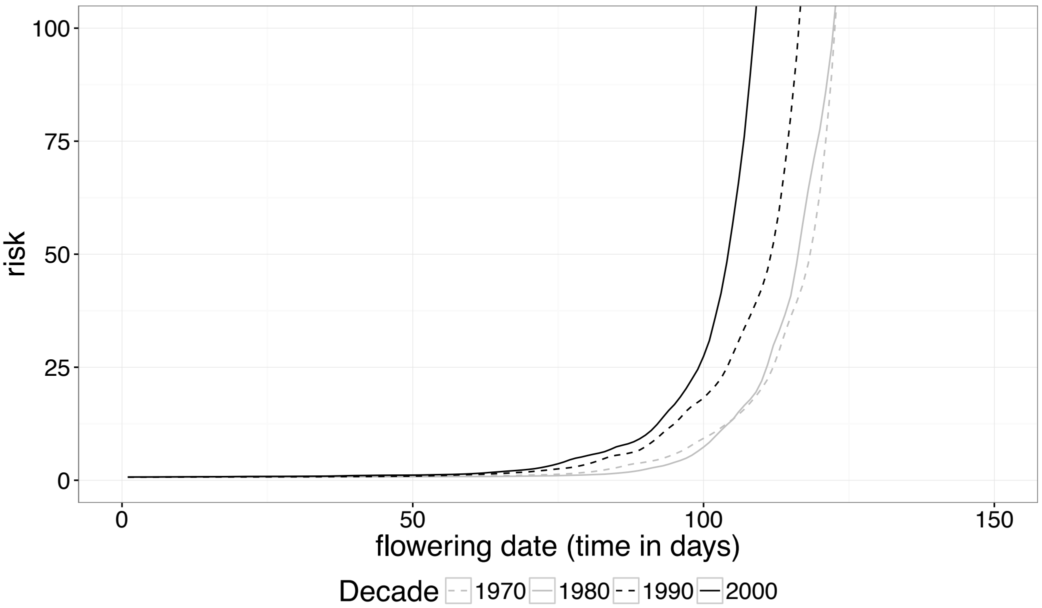

Figure 4.3: Relative flowering risk of *Taraxacum officinale* averaged by decades.

Prediction of the flowering date

For comparison purposes we predicted the mean flowering date from a classical linear regression model, as well as from a Cox model with and without time dependent covariates. The Cox model itself does not directly predict a flowering date based upon given predictor variables (station, GDD, precipitation), but rather gives the probability that plants have not yet flowered by a given day. The mean predicted flowering date we use for our prediction is the date where there is a 50% percent chance that the plant has flowered.

The results are visualized in Figure 4.4. The predicted mean flowering of *T. officinale* correlated the best with the observed dates for the Cox model with time dependent covariates (≈ 0.89, see Figure 4.4). Naturally, model deviations are highest for observations that depart from the bulk of the data. In our case, this mainly occurred with observed flowering dates earlier than day 45 and a few late flowering dates.

According to Figure 4.4, it becomes obvious that the Cox model, especially the one with time dependend covariates (bottom right), gives better fit also to the extremes of the distribution as the traditional linear regression model (top right). Table 4.2 shows several estimates of prediction accuracy based on stratified fivefold cross validation. We can see that the Cox model for time dependent covariates outperforms the other models in terms of the root mean square error (RMSE), the mean absolute error (MAE) and the mean absolute percentage error (MAPE).

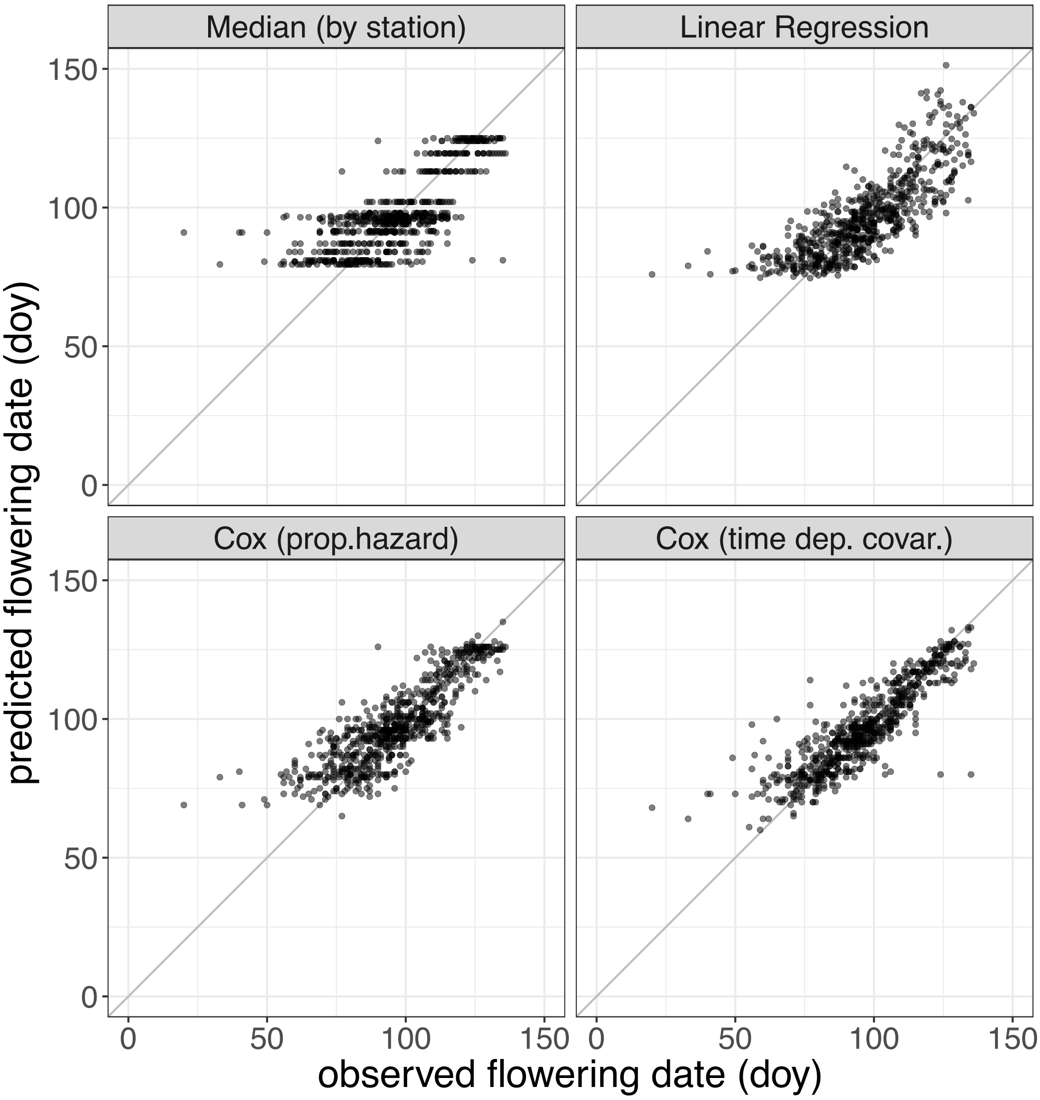

Figure 4.4: Predicted against observed mean flowering dates (doy) of *Taraxacum officinale*. For comparative purposes the four cases indicate results from the median observed doys for each station against original observations (Median), the traditional regression model (Linear Regression), the Cox model without time dependent covariates (Cox (prop.hazard)) and the Cox model with time dependent covariates (Cox (time dep. covar.)).

Table 4.2: Estimation of prediction accuracy using fivefold cross validation for the following models: (1) the median of the observed flowering date of each station (baseline model), (2) a simple linear regression model (classical modelling approach), (3) the Cox proportional hazard model (without time dependent covariates), and (4) the Cox model with time dependent covariates. Abbreviations: RMSE = root mean squared error, MAE = mean average error, MAPE = mean average percentage error.

	RMSE	MAE	MAPE
median	12.84	9.72	10.51
regression	11.01	8.52	9.10
cox (prop.hazard)	11.71	8.92	9.53
cox (time dep. covar.)	10.46	7.44	8.07

4.4 Discussion

Plant phenological responses are well documented across the Northern Hemisphere (Menzel *et al.*, 2006; Schwartz *et al.*, 2006) since such phenomena are sensitive to variations in climate, especially to temperature, as highlighted by recent studies on the ecological consequences of global climate change. Observed climate trends and future scenarios show regionally varying changes in temperature and precipitation in Europe (Kovats *et al.*, 2014). Temperature increase in the Alpine region is expected to accelerate in the next century (Gobiet *et al.*, 2014). We also detected warming trends (1970–2010) in 2 (Alpine and continental) of the studied 5 biographical regions in Europe (see Figure 3.2).

Predictions of future warming necessitate further development of tools to better understand plant phenological responses, and this includes the testing of potentially useful non-traditional methods. Relative risk is a known terminology in epidemiology to describe the likelihood of developing a disease, as well as in environmental management to assess ecological risk. We present an application of this approach to the prediction of flowering time, by calculating the probability of flowering onset date by survival modeling. In general, survival models investigate follow-up time from a defined starting point to the occurrence of a given event (Bewick *et al.*, 2004).

Compared to traditional linear regression, a major difference, and advantage of survival models is the possibility of including time dependent (time-varying) covariates. These are predictor variables (in our case GDD and precipitation) whose values may change over the course of observation. Classical phenological models estimate plant developments by accumulating degree days between temperature thresholds throughout the season. The accumulation of degree days from a starting point can help to predict when a phenological stage will be reached. Similarly, survival models are able to integrate more environmental variables, but without the requirement to aggregate them. This is advantage, because the usage of daily data (Pau *et al.*, 2011) and the avoidance of the modifiable temporal unit problem (Jong and Bruin, 2012). Based on the assumption that the probability of a phenological event happening can be interpreted as a survival event, we calculated the relative risk of flowering time for *T. officinale* across biogeographical regions in Europe. To our knowledge, this method has only been tested on bird phenological data (Gienapp *et al.*, 2005, 2010; Visser *et al.*, 2006; Williams *et al.*, 2015) so far. Thus, the potential of this application is yet to be recognised by the plant phenological community.

Zeng *et al.* (2011) investigated recent changes in phenology over Northern high latitudes from multi-satellite data. They found that the period 2000–2010 was associated with an advanced start of the growing season (SOS) of larger magnitude than the SOS trends of the 1980s and 1990s. Similarly to these findings, based on Kaplan-Meier estimation, we have found that within each decade since the 1980s, the timing of flowering of *T. officinale* has shifted towards earlier dates in Europe. By introducing survival curves to phenological research, it is possible to compare the timing of phenological phases by decades, locations and species. There is potential in the development of the method to estimate the change in phenological phases under various climate scenarios (Gienapp *et al.*, 2005).

There is evidence from a wide range of taxa and across a wide range of geographic locations that phenological events in spring have been happening earlier in recent decades (Sparks and Menzel, 2002; Parry *et al.*, 2007). As is the case for most of the spring phenophases, the flowering date of *T. officinale* exhibits a stronger phenological response to temperature in warmer than in colder countries (Menzel *et al.*, 2006; Jatczak and Walawender, 2009). But what are the driving factors of such response? Phenology uses environmental cues to attune flowering to appropriate seasonal conditions (Tookey and Battey, 2010). Several covariates (North Atlantic Oscillation, precipitation, temperature, photoperiod, snowmelt) have been determined as appropriate predictors for flowering onset. In the case of *T. officinale* we documented no significant influence of precipitation on the timing of flowering across biogeographical regions in Europe. Fu *et al.* (2014) showed that the GDD requirement for vegetation green-up onset plays an important role at higher latitudes along the geographical coordinates of 35° – 70°. Our findings confirm the significant effect of GDD on plant phenology (Cox, 1972).

We aimed, not just to give a spatio-temporal description of climatic drivers of flowering onset dates across Europe, but also to compare various models that can be used to predict phenological events. The forecasting of ecological responses to climate change represents a major challenge for many reasons (Cook *et al.*, 2010), such as systematic errors in simulations (Migliavacca *et al.*, 2012). Our work demonstrated that Cox models can compete with traditional regression models or even outperform them. We find that survival models can be a fruitful extension to well-established traditional approaches in phenology. However the approach needs further testing, to assess whether it can be generalized for any other phenophase of living organisms.

CHAPTER 5

Testing plant phenophase as proxy: sensitivity analysis of first flowering data from the 19th century*

Abstract

Eco-climatological studies recognise plant phenophases as high-confident climate indicators, since they are strongly dependent on heat conditions. We investigated the first flowering response of numerous plant species to inter-annual fluctuation of seasonal temperatures (e.g., heat sensitivity of the phenophase), also the rate of these species-specific sensitivities in order to test their applicability as proxy of temperature. From the few available data sources recorded in the Carpathian Basin during the 19th century, the first flowering data sets of 16 plant species

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*The paper co-authored with Annamária Lehoczky, Rita Pongrácz and Ferenc Szentkirályi (Lehoczky *et al.*, 2016) is published in *Applied Ecology and Environmental Research.*

and time series of monthly mean temperature (site: Hermannstadt; period: 1851-1891) were selected for the analysis. We found that the first flowering dates of different plants fluctuated significantly synchronously, however, temporal trends were not detected in any of the time series. Based on the main heat sensitivity characteristics, the species were ranked as phyto-thermometers to select the best heat indicator plants. The first flowering data of these indicators were applicable to estimate temperature data. The accuracy of different plants as proxies varied in the range of 1.0 °C and 1.5 °C. Therefore our procedure is of interest in order to better understand past climates of periods or locations, where no instrumental records are available.

5.1 Introduction

The Earth is already experiencing human induced global scale climatic changes, which affect the whole biosphere. The number of evidences are increasing according to the biological responses documented (Walther *et al.*, 2002; Parmesan and Yohe, 2003; Root *et al.*, 2003; Bartholy *et al.*, 2012) in plant and animal populations. The most easily detectable and widely reported changes can be seen worldwide in the timing of phenological events (Miller-Rushing and Primack, 2008). Several studies have been gathered from the past half-century about spatial and temporal shifts of plant phenophases associated with global warming trends. Evidences of plant phenological responses are known across the globe (Badeck *et al.*, 2004; Cleland *et al.*, 2007; Elzinga *et al.*, 2007), from the Northern (Schwartz *et al.*, 2006) to the Southern Hemisphere (Chambers *et al.*, 2013), towards Europe (Fitter *et al.*, 1995; Ahas and Aasa, 2006; Menzel *et al.*, 2006), Russia (Ovaskainen *et al.*, 2013) and China (Ge *et al.*, 2015). Thus, one of the most appropriate indicators of climatic changes is the phenophase of living beings. Phenology, the science of natural recurring events (Demarée and Rutishauser, 2011) analyses the timing of periodic life-history events (i.e. phenophases) such as budburst or first flowering of plants (Pau *et al.*, 2011). Specifically, the first definition by Lieth (1974) says: 'Phenology is the study of timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species'.

In moderate and cold climatic zones, phenological phases occure in the spring season are particularly sensitive to their environment. Adaptation to inter-annual day length of these phenophases can cause detectable changes in their growth activity if they are reinforced by increasing temperature (Rutishauser *et al.*, 2007). Atmospheric teleconnection patterns, e.g. the North Atlantic Oscillation, influence both temperature and precipitation conditions of the Northern Hemisphere (Trigo *et al.*, 2002; Hurrell *et al.*, 2003; Bartholy *et al.*, 2009a; Mándl, 2009), and thus, indirectly the phenological patterns, too (Menzel, 2003; Stenseth *et al.*, 2003). Precipitation cannot be considered as a major driving factor at the mid-latitudes (Buermann *et al.*, 2003), because it usually does not significantly explain variances of the spring plant development (Rutishauser *et al.*, 2007). However, it is more important in arid and semi-arid regions (Lima and Rodal, 2010).

Eco-climatological studies refer to plant phenophases can often be used as bio-indicators of climate change or proxies for temperature (Menzel, 2002, 2003; Miller-Rushing *et al.*, 2008), especially when the seasonal timing of the phenological event is closely related to specific climatic conditions during plant development (Aono and Kazui, 2008; Sparks *et al.*, 2000). The so-called climate proxies are preserved physical characteristics of the past that stand for direct measurements and can be utilized for climatological reconstructions (Rutishauser *et al.*, 2007). Furthermore, vice versa, future climate projections can be used for the prediction of the proxy based on the strong relationship between the variables. Numerous studies reconstructed temperature conditions using different phenophases from available phenological data series (e.g., Holopainen *et al.*, 2006; Lavoie and Lachance, 2006; Rutishauser *et al.*, 2007; Aono and Kazui, 2008; Kiss *et al.*, 2010). Although phenological data series compiled from historical records allow climate reconstructions on shorter time-scale compared to other proxies (such as tree ring, pollen or ice core data), they are also important sources for the analysis of past climate and cross-validation (Dickinson and Bonney, 2012). Detailed analyses of heat sensitivity of different phenophases were carried out in Germany, Switzerland and UK (Rutishauser *et al.*, 2009; Schleip *et al.*, 2009), but not yet for the Carpathian Basin.

The enhanced protection of plant species and their habitats under climatic changes is substantial in the, otherwise they might face to severe consequences and even extinction (Root *et al.*, 2003; Thuiller *et al.*, 2005; Estes *et al.*, 2011). In order to understand and predict the impact of current climatic changes on plant phenophases, it is necessary to analyse phenological time series as a reference from the period when the recent anthropogenic warming effect did not influence the local climate conditions. Unfortunately, most of the phyto-phenological data series recorded in the 19th century, suffer lacks both in time and space for the Carpathian Basin (Szalai *et al.*, 2008). The available studies from this region (e.g., Walkovszky, 1998; Varga *et al.*, 2009a,b, 2010; Szabó *et al.*, 2016) rely on phenological data series recorded at the second half of 20th century, which period is already significantly influenced by the warming spring (Pongrácz *et al.*, 2011; Cramer *et al.*, 2014).

In the present study, we investigated the first flowering response of 16 wild plant species to interannual fluctuation of local seasonal temperatures (i.e., heat sensitivity of the flowering onset), also the rate of these species-specific sensitivities in order to test their applicability as proxy of temperature. The analyses were accomplished using first flowering data series, recorded in the second half of the 19th century, in Hermannstadt and Mediasch located in Transylvania (nowadays in Romania). The following issues were addressed using different statistical methods: (i) characterization of the effect of mean temperatures in various time periods (monthly, bi-monthly, tri-monthly, etc) on flowering onset dates using a moving-window technique; (ii) determination of the effective temperature values (T_{eff}) estimated from the responses of each species; (iii) calculation of the temporal shifts of first flowering date as a response to T_{eff}. Furthermore, (iv) the plant species were ranked based on the temperature sensitivity of their first flowering dates; and (v) the accuracy of use of plant phenophases as proxy estimations was evaluated.

5.2 Materials and methods

Phenological data

The analyses are accomplished using flowering onset data sets of 16 wild plant species (Table 5.1) recorded in the second half of the 19th century. The observations were carried out in the period 1851–1891, near Hermannstadt (45°48' N, 24°9' E, named Sibiu today, located in Romania), by Ludwig Reissenberger, a local teacher deeply interested in natural science. The data records are considered reliable and the documentation is precise due to the unchanged observer.

In order to test the accuracy of flowering dates as proxy, data from Mediasch (46°10' N, 24°21' E, named Mediaş today, located at cc. 50 km distance from Hermannstadt) have also been involved into analyses for the period 1854–1865. (All the data mentioned above are available in the Austro-Hungarian and Hungarian Meteorological Yearbooks.) At both sites, the date of flowering onset was defined as the date when some individuals from the whole plant population were totally

Table 5.1: Flowering onset data characteristics of the observed 16 plant species near Hermannstadt in the period 1851–1891 (SD=standard deviation; *herbaceous plants).

	Species names		**Flowering onset (FO)**		
			Mean FO date	**Days after 1 January**	**±SD [day]**
Sp-1	*Tussilago farfara* L.	Coltsfoot*	02 March	62	15.7
Sp-2	*Scilla bifolia* L.	Two-leaf squill*	25 March	85	10.0
Sp-3	*Taraxacum officinale* W.	Common dandelion*	05 April	96	12.0
Sp-4	*Caltha palustris* L.	Marsh marigold*	07 April	98	9.1
Sp-5	*Salix fragilis* L.	Crack willow	16 April	106	9.9
Sp-6	*Ribes rubrum* L.	Red currant*	20 April	110	9.0
Sp-7	*Fragaria vesca* L.	Woodland strawberry*	23 April	113	8.9
Sp-8	*Orchis morio* L.	Green-winged orchid*	01 May	122	8.2
Sp-9	*Syringa vulgaris* L.	Common lilac	02 May	123	8.8
Sp-10	*Aesculus hippocastanum* L.	Horse chestnut	04 May	125	8.5
Sp-11	*Euonymus europaeus* L.	European spindle	07 May	128	8.1
Sp-12	*Salvia pratensis* L.	Meadow sage*	10 May	130	8.7
Sp-13	*Dianthus carthusianorum* L.	Carthusian pink*	24 May	144	9.3
Sp-14	*Robinia pseudoacacia* L.	Black locust	25 May	145	9.1
Sp-15	*Sambucus nigra* L.	Black elder	26 May	146	9.3
Sp-16	*Vitis vinifera* L.	Common grape vine	13 June	165	7.3

flowering as it was given by the protocol of phenological observation in the 19th century (see in Meteorological Yearbooks). At Hermannstadt 24 plant species were observed by Reissenberger, however for detailed analyses 16 species were selected based on two criteria: (i) the plant was required to be common, widespread and possibly wild, in order to identify them by the observer easily, (ii) the average first flowering date was required to occur in the period from late-winter/early-spring until early-summer to enable comparisons of species-specific responses to different seasonal temperatures. According to similar investigations (Menzel, 2002, 2003;

Fitter and Fitter, 2002), these early flowering species are more sensitive to climatic variations than the later (summer and/or autumn) flowering ones. In addition, half of the selected 16 species were herbaceous plants and the others were woody. The date of phenophase was given as the 'day of the year', i.e., the number of days elapsed since 1st January of a given calendar year (doy).

Climatological data

The time series of monthly mean temperatures were also obtained from the mentioned Meteorological Yearbooks, and covered the same period (1851-1891 and 1854-1865) as the phenological observations originated from the two observational sites. The monthly means of air temperature were calculated from daily data. These daily time series were averaged and corrected from three daily measurements, recorded in the yearbooks. The meteorological measurements were carried out by standard devices of the Austrian weather service. Detailed descriptions of the measuring methods, conditions, devices, and applied corrections can be found in the yearbooks. After transforming the Réaumur degrees into standard Celsius degrees, and completing quality control, the monthly averaged data sets were considered as local homogeneous time series.

Statistical methods

Both phenological and temperature data sets can be characterized by normal distribution, which was checked with Kolmogorov-Smirnov statistical test using 95% confidence interval.

Linear regression analyses were applied to describe the possible long-term trends in the time series and possible relations between temperature and phenological data. The goal was to identify linear trend via regression of the observed time series against time and test the estimated slope coefficient of the linear regression equation for significance (Haan, 2002). The well-known least squares method was used for parameter estimation.

Cross correlation function (CCF) was calculated between the two time series (y_t: phenological and x_t :climatic) for identifying lags of the x-variable that might be useful predictors of y_t. CCF was defined as the set of sample correlations between x_{t+l} and y_t for $l = 0$. Cross correlation values reflect the degree of linear relationship between the two data sets. Significant negative values for r_0 show if there was a negative correlation between the x-variable and the y-variable at time t with 0-lag (confirmed by t-test with 0.95 level of significance).

In phenological analyses, climatic variables are usually aggregated into averages over a month or more. Despite the loss of information due to aggregation, this aggregating method was applied in order to avoid both numerical problems and difficulties with interpretation arising from the high dimensional and correlated nature of daily weather data (Roberts, 2010). In this study bi-, tri-, and tetra-monthly mean temperatures were calculated from the monthly mean data to examine the relationships between the timing of first flowering and temperature data.

The effective temperature ($\mathrm{T_{eff}}$) is a nominal temperature that represents the heat conditions of the period, which is considered to possess the highest impact on the timing of flowering onset of a plant species. So, the $\mathrm{T_{eff}}$ values represent different heat conditions due to different length of aggregating periods. The effective temperature periods were found by a 'moving window' technique: bi-, tri-, and tetra-monthly temperatures were calculated from the monthly means by shifting 1-month-steps. As a result of this method, newly aggregated time series were obtained such as $\mathrm{T_{FM}}$, $\mathrm{T_{MA}}$, $\mathrm{T_{AM}}$, $\mathrm{T_{MJ}}$; $\mathrm{T_{JFM}}$, $\mathrm{T_{FMA}}$, $\mathrm{T_{MAM}}$, $\mathrm{T_{AMJ}}$; and $\mathrm{T_{JFMA}}$, $\mathrm{T_{FMAM}}$, $\mathrm{T_{MAMJ}}$ – in the subscripts the first letter of months is given. The heat conditions of the winter-spring period prior to the time of flowering (even the previous summer and autumn conditions) can significantly influence as well as determine the date of flowering onset (Miller-Rushing and Primack, 2008). Hence the average temperatures of these periods can be considered as rough representation of the cumulative amount of heat. We determined the most effective temperature period for the phenophase of each species, by calculating serial CCF values. The most effective temperature period for a certain plant was selected by the highest absolute value of r_0 (see details on Figure 5.4).

The temporal shifts of first flowering date as a response to T_{eff} and the heat sensitivity were described after applying linear regression. These characteristics were determined from the slope of the regression equations between the flowering and temperature time series. The regression coefficients indicate the effect (shift of flowering onset in days) of 1°C change in temperature in the certain period. Negative value of the regression coefficient indicates the advancement of flowering in response to increasing temperature.

To describe the species-specific relative response of flowerings to relative changes in T_{eff}, both data series were converted into relative measures (expressed in percentages). These were obtained as follows: (i) determination of the anomalies of time series compared to the average of time series, (ii) sum of these anomalies without signs (this sum means the 100%), and finally (iii) expression the anomalies with signs as a percent of the previously calculated amount of 100%. The obtained relative responses of flowerings were considered as rough indicators of heat sensitivity characterising the plant species. By this indicator the plants were ranked and compared in terms of possible utilization as proxy.

In order to test the flowering onset of the selected plants as proxy data for local average seasonal temperatures (assuming relatively constant heat sensitivity in at least 50 km vicinity of the Hermannstadt site), phenological and temperature data of Mediasch (period: 1854–1865) were involved into the analysis. In case of 14 plant species observed at both places, by replacing the phenological data of Mediasch into the regression equation established on the relation between the phenological and temperature data of Hermannstadt, a robust estimation of local effective temperature was gained. The statistical analysis was carried out with codes written in FORTRAN language and with the *Statistica* 6.1 software (StatSoft, 2003).

5.3 Results

Characteristics of studied time series

Observed temperature data According to the completed trend analysis, significant temporal trend was not detected in any of the temperature time series of Hermannstadt (1851–1891) and Mediasch (1854–1865), except mean temperature of April at Hermannstadt ($p < 0.05$), which was detrended for further analyses. After comparing monthly temperature data of the two locations, Mediasch was warmer than Hermannstadt by 1.04 °C on a yearly basis. Such difference could be resulted from the microclimates caused by differences in topographical conditions. Nevertheless, the general temperature conditions are quite similar at both places. Based on the preliminary analysis (data not shown), the early spring temperature series were significantly synchronously fluctuating at the two sites in the same period.

Overview of flowering onset data The means of flowering onset dates with their standard deviations are listed for each species in Table 5.1. The order of plant species listed in Table 5.1 are based on increasing mean FO dates. Accordingly, numbers were given for each studied species (Sp1–Sp16), which provide reference for the species indicated on many Figures of this Chapter 5.

Standard deviation (SD) of the first flowering date was decreasing from the earlier to later flowering plants due to the higher variability of mean temperatures in cooler months (January–March) (Figure 5.1). The earliest spring flowering plant was *T. farfara*, which was characterized by relatively high SD (15.7 days) and total range (75 days). In contrast, the early summer flowering *V. vinifera* had the lowest SD among the examined species and significantly lower range (47 days) than the others. The group of early May flowering plants (i.e., *O. morio, S. vulgaris, A. hippocastanum* and *E. europaeus*) as well, as the group of late May flowering species (i.e., *D. carthusianorum, R. pseudoacacia* and *S. nigra*) were characterized by similarly high minimum, maximum and SD values within the groups (Table 5.1).

Significant temporal trend was not detected in any of the time series. Based on the CCF values, flowering time series significantly synchronously fluctuated not just intralocally (between species), but interlocally (between locations) as well. In order to illustrate this synchrony, the temporal patterns of FO of four plants are drawn in Figure 5.2. The sharp yearly fluctuation of *T. farfara* (Sp-1) – as the earliest flowering plant – is conspicuous, indicating a strong sensitivity to late-winter temperatures.

Impact of temperature on flowering onset In order to determine the strength of the relationship between the timing of flowering onset and temperature data, correlation coefficients (r_0) at 0 lag CCFs were calculated (Table 5.2). To determine the T$_{eff}$ period the moving window method was applied on monthly data from the previous June until the July of the actual year regarding the occurrence of phenophase. The signs of r_0 were mostly negative in case of winter-spring months, indicating that plants responded to higher temperatures with earlier flowering onsets (Figure 5.3).

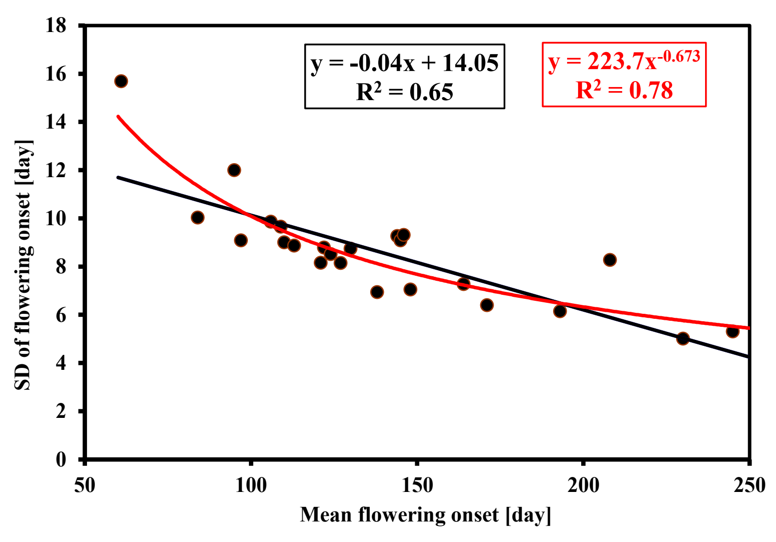


Figure 5.1: Relationship between mean flowering onsets and their standard deviations (SD) in case of plants observed (1851–1891) near Hermannstadt. Both linear and exponential regressions clearly show significant decrease of SD towards the late flowering plant species.

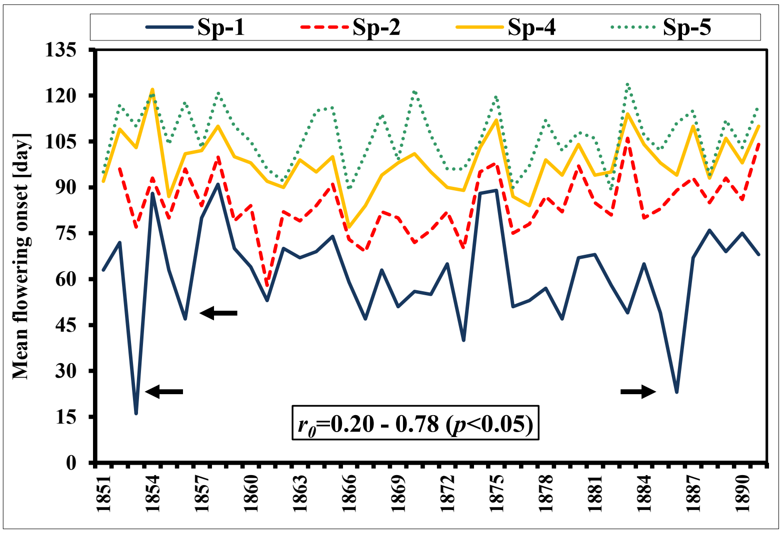


Figure 5.2: The synchronous fluctuations of four early flowering plants near Hermannstadt (1851–1891). The value of correlation coefficient (r_0) was higher between the later ones, *S. bifolia* (Sp-2), *C. palustris* (Sp-4) and *S. fragilis* (Sp-5), than the earliest flowering *T. farfara* (Sp-1). The black arrows point at the marked deviations of Sp-1 due to late winter heat waves.

In late winter – spring seasons, strong correlations ($p < 0.05$) were found between the flowering onset data series and monthly, multi-monthly mean temperature time series in case of most species (indicated in bold in Table 5.2). Effective temperatures of 16 plant species were determined by serial correlations using the 'moving window' method described above (Section 5.2).

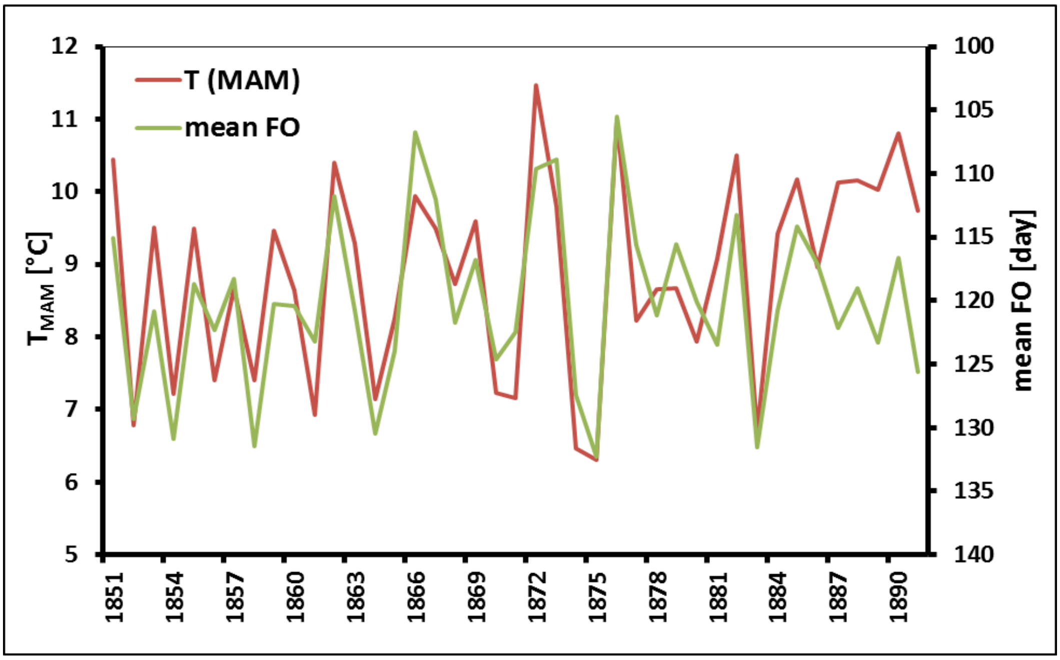
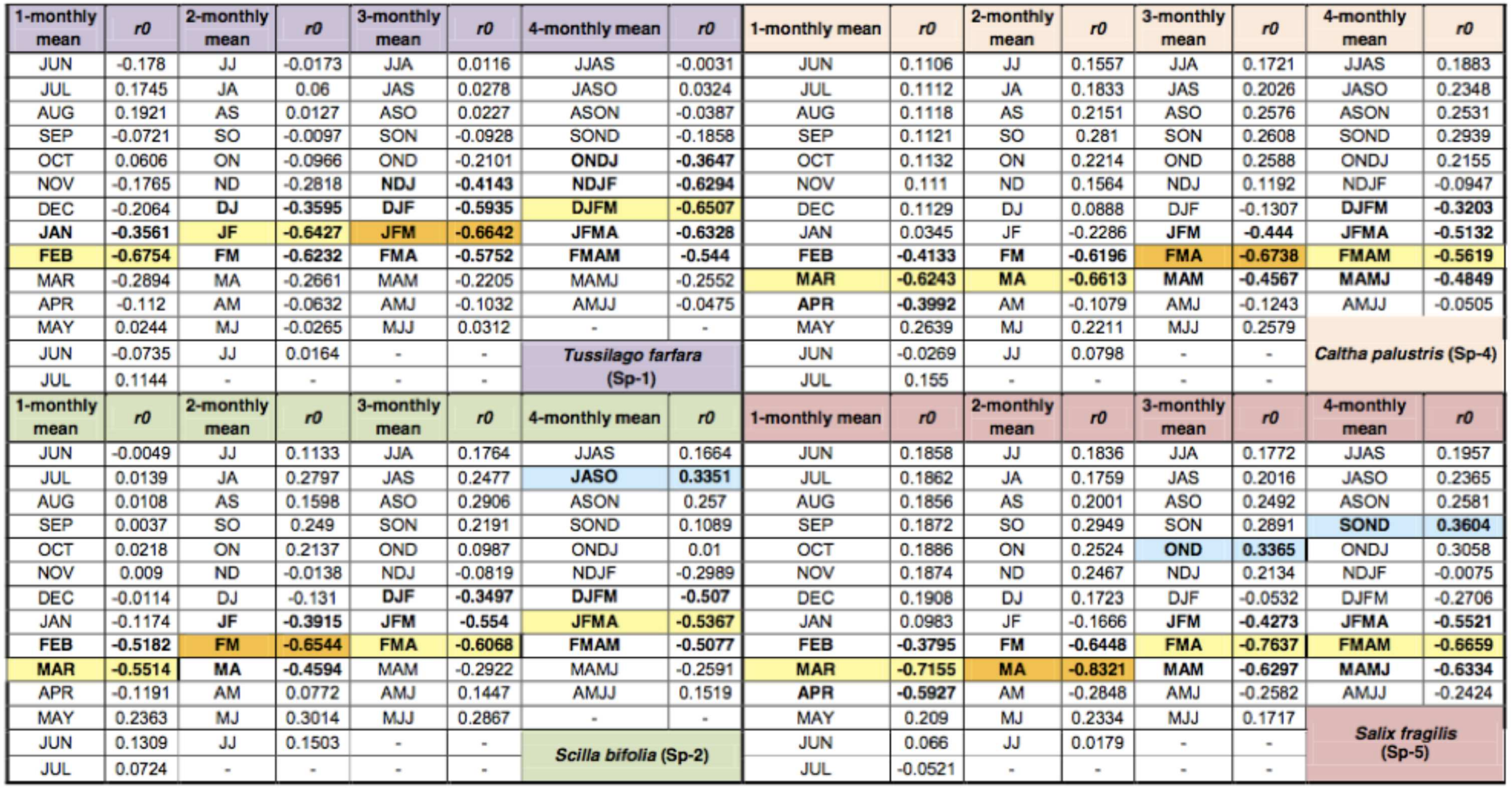


Figure 5.3: Mean flowering onset (FO) of 16 plant species and tri-monthly mean temperature of the period March–May recorded near Hermannstadt (1851–1891).

Periods of the effective temperature (T_{eff}) and periods with high FO-T correlation ($r_0 > 0.5$) are given in Table 5.3 for the 16 examined plant species. The majority of plants expressed the highest correlation with the bi-monthly mean temperature preceding the flowering onset, however there were some examples, which produced the highest r_0 with tri-monthly period (e.g. *T. farfara* – JFM) or even longer, tetra-monthly period (e.g. *V. vinifera* – MAMJ). In case of almost all plants the DJFM and the JFMA periods were the first 'negative-effect' (i.e. causing advanced FO) periods, while for *T. farfara* and *T. officinale* the mean

Table 5.2: Four examples (Sp-1: *T. farfara*, Sp-2: *S. bifolia*, Sp-4: *C. palustris*, and Sp-5: *S. fragilis*) for finding the period of most effective temperature (T_{eff}) of flowering onsets using serial cross correlation functions (CCF) and moving window technique with different number (1, 2, 3 and 4) of months. Legend: bold numbers: significant correlation coefficient value (r_0) ($p < 0.05$); pale yellow cell: the highest correlation coefficient in the column; orange cell: the highest correlation coefficient for the plant, so it reflects to the effective temperature period; blue cell: significant influence of the previous year.



1-monthly mean	***r0***	**2-monthly mean**	***r0***	**3-monthly mean**	***r0***	**4-monthly mean**	***r0***	**1-monthly mean**	***r0***	**2-monthly mean**	***r0***	**3-monthly mean**	***r0***	**4-monthly mean**	***r0***
JUN	-0.178	JJ	-0.0173	JJA	0.0116	JJAS	-0.0031	JUN	0.1106	JJ	0.1557	JJA	0.1721	JJAS	0.1883
JUL	0.1745	JA	0.06	JAS	0.0278	JASO	0.0324	JUL	0.1112	JA	0.1833	JAS	0.2026	JASO	0.2348
AUG	0.1921	AS	0.0127	ASO	0.0227	ASON	-0.0387	AUG	0.1118	AS	0.2151	ASO	0.2576	ASON	0.2531
SEP	-0.0721	SO	-0.0097	SON	-0.0928	SOND	-0.1858	SEP	0.1121	SO	0.281	SON	0.2608	SOND	0.2939
OCT	0.0606	ON	-0.0966	OND	-0.2101	**ONDJ**	**-0.3647**	OCT	0.1132	ON	0.2214	OND	0.2588	ONDJ	0.2155
NOV	-0.1765	ND	-0.2818	**NDJ**	**-0.4143**	**NDJF**	**-0.6294**	NOV	0.111	ND	0.1564	NDJ	0.1192	NDJF	-0.0947
DEC	-0.2064	**DJ**	**-0.3595**	**DJF**	**-0.5935**	**DJFM**	**-0.6507**	DEC	0.1129	DJ	0.0888	DJF	-0.1307	**DJFM**	**-0.3203**
JAN	**-0.3561**	**JF**	**-0.6427**	**JFM**	**-0.6642**	**JFMA**	**-0.6328**	JAN	0.0345	JF	-0.2286	**JFM**	**-0.444**	**JFMA**	**-0.5132**
FEB	**-0.6754**	**FM**	**-0.6232**	**FMA**	**-0.5752**	**FMAM**	**-0.544**	**FEB**	**-0.4133**	**FM**	**-0.6196**	**FMA**	**-0.6738**	**FMAM**	**-0.5619**
MAR	-0.2894	MA	-0.2661	MAM	-0.2205	MAMJ	-0.2552	**MAR**	**-0.6243**	**MA**	**-0.6613**	**MAM**	**-0.4567**	**MAMJ**	**-0.4849**
APR	-0.112	AM	-0.0632	AMJ	-0.1032	AMJJ	-0.0475	**APR**	**-0.3992**	AM	-0.1079	AMJ	-0.1243	AMJJ	-0.0505
MAY	0.0244	MJ	-0.0265	MJJ	0.0312	-	-	MAY	0.2639	MJ	0.2211	MJJ	0.2579	***Caltha palustris* (Sp-4)**	
JUN	-0.0735	JJ	0.0164	-	-	***Tussilago farfara* (Sp-1)**		JUN	-0.0269	JJ	0.0798	-	-		
JUL	0.1144	-	-	-	-			JUL	0.155	-	-	-	-		

1-monthly mean	***r0***	**2-monthly mean**	***r0***	**3-monthly mean**	***r0***	**4-monthly mean**	***r0***	**1-monthly mean**	***r0***	**2-monthly mean**	***r0***	**3-monthly mean**	***r0***	**4-monthly mean**	***r0***
JUN	-0.0049	JJ	0.1133	JJA	0.1764	JJAS	0.1664	JUN	0.1858	JJ	0.1836	JJA	0.1772	JJAS	0.1957
JUL	0.0139	JA	0.2797	JAS	0.2477	**JASO**	**0.3351**	JUL	0.1862	JA	0.1759	JAS	0.2016	JASO	0.2365
AUG	0.0108	AS	0.1598	ASO	0.2906	ASON	0.257	AUG	0.1856	AS	0.2001	ASO	0.2492	ASON	0.2581
SEP	0.0037	SO	0.249	SON	0.2191	SOND	0.1089	SEP	0.1872	SO	0.2949	SON	0.2891	**SOND**	**0.3604**
OCT	0.0218	ON	0.2137	OND	0.0987	ONDJ	0.01	OCT	0.1886	ON	0.2524	**OND**	**0.3365**	ONDJ	0.3058
NOV	0.009	ND	-0.0138	NDJ	-0.0819	NDJF	-0.2989	NOV	0.1874	ND	0.2467	NDJ	0.2134	NDJF	-0.0075
DEC	-0.0114	DJ	-0.131	**DJF**	**-0.3497**	**DJFM**	**-0.507**	DEC	0.1908	DJ	0.1723	DJF	-0.0532	DJFM	-0.2706
JAN	-0.1174	**JF**	**-0.3915**	**JFM**	**-0.554**	**JFMA**	**-0.5367**	JAN	0.0983	JF	-0.1666	**JFM**	**-0.4273**	**JFMA**	**-0.5521**
FEB	**-0.5182**	**FM**	**-0.6544**	**FMA**	**-0.6068**	**FMAM**	**-0.5077**	**FEB**	**-0.3795**	**FM**	**-0.6448**	**FMA**	**-0.7637**	**FMAM**	**-0.6659**
MAR	**-0.5514**	**MA**	**-0.4594**	MAM	-0.2922	MAMJ	-0.2591	**MAR**	**-0.7155**	**MA**	**-0.8321**	**MAM**	**-0.6297**	**MAMJ**	**-0.6334**
APR	-0.1191	AM	0.0772	AMJ	0.1447	AMJJ	0.1519	**APR**	**-0.5927**	AM	-0.2848	AMJ	-0.2582	AMJJ	-0.2424
MAY	0.2363	MJ	0.3014	MJJ	0.2867	-	-	MAY	0.209	MJ	0.2334	MJJ	0.1717	***Salix fragilis* (Sp-5)**	
JUN	0.1309	JJ	0.1503	-	-	***Scilla bifolia* (Sp-2)**		JUN	0.066	JJ	0.0179	-	-		
JUL	0.0724	-	-	-	-			JUL	-0.0521	-	-	-	-		

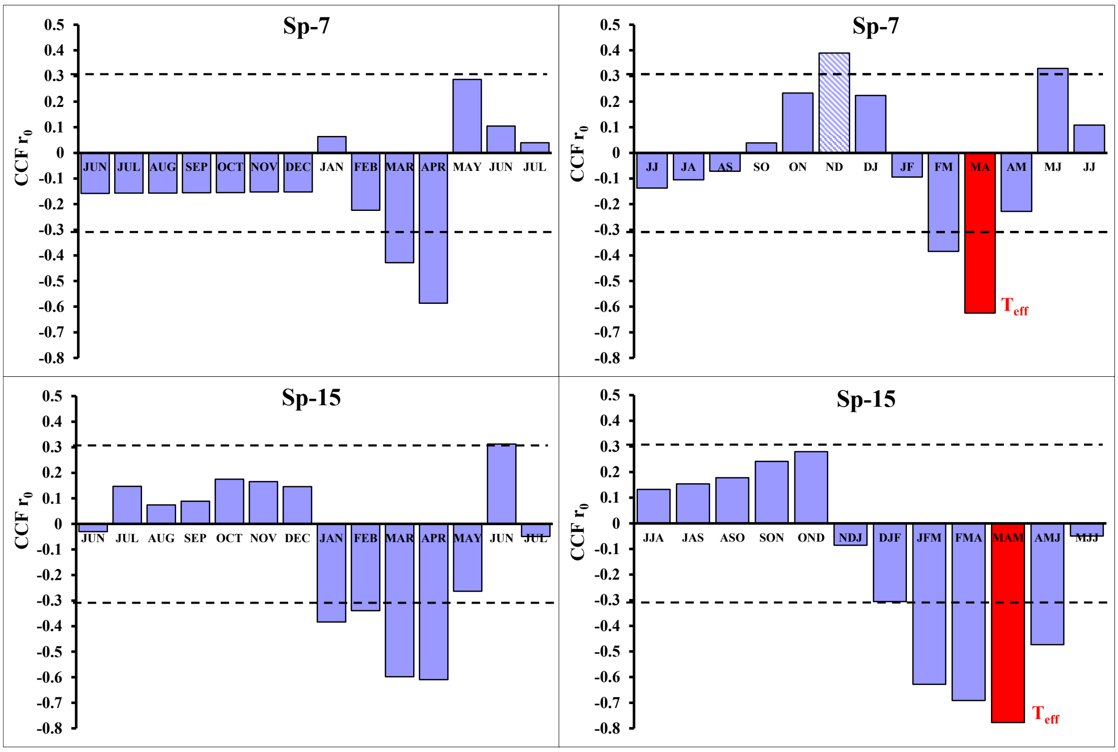


Figure 5.4: Two examples (Sp-7: *F. vesca* and Sp-15: *S. nigra*) for finding the most effective temperature (T_{eff}) of flowering onsets using serial cross correlation functions (CCF) and moving window technique with different number (1, 2, 3 and 4) of months. Scattered lines on the graphs indicate the threshold of significant ($p < 0.05$) correlation coefficient values (r_0).

temperature of the late autumn – winter (ONDJ, NDJF) period was found to be also significantly effective on the timing of subsequent flowering onset (Table 5.2).

For half of the species a 'positive effect' (i.e. causing delayed FO) by the multi-monthly mean temperatures of previous years in summer-autumn season was observed. In case of eight plants, significant ($p < 0.05$) positive values of r_0 were found, associated with relation to bi-, tri-, tetra-monthly summer – autumn mean temperatures and the mean flowering onset. The FO of *S. bifolia* was influenced by the mean temperature of late summer – early autumn period; similarly the FO of *S. fragilis, S. vulgaris, D. carthusianorum* and *R. pseudoacacia* by the mean

Table 5.3: The effective temperature (T_{eff}) periods and the 1-month periods of temperature with the highest influence (r >0.5; p<0.05) on the timing of flowering onset (FO) of the 16 studied plant species observed near Hermannstadt (1851–1891).

Species	**Period of T_{eff} (multi-month)**	**Correlation $F0-T_{month}(r>0.5)$**
Tussilago farfara	JFM	Feb
Scilla bifolia	FM	Feb, Mar
Taraxacum officinale	FM	Mar
Caltha palustris	FMA	Mar
Salix fragilis	MA	Mar, Apr
Ribes rubrum	MA	Mar, Apr
Fragaria vesca	MA	Apr
Orchis morio	MA	Mar, Apr
Syringa vulgaris	MA	Apr
Aesculus hippocastanum	MA	Apr
Euonymus europaeus	MA	Mar, Apr
Salvia pratensis	A, MA	Apr
Dianthus carthusianorum	MAM	Apr
Robinia pseudoacacia	AM	Apr, May
Sambucus nigra	MAM	Mar, Apr
Vitis vinifera	MAMJ	Apr, May

temperature of autumn period; and FO of *F. vesca* by the mean temperature of late autumn – winter period were affected as well. Finally, for *A. hippocastanum* the FO seemed to be influenced by the temperature conditions of the entire June to December period.

Species-specific heat sensitivity of flowering onset

Flowering sensitivities of the selected plants in response to their effective temperatures were different. Based on results of the regression analysis (RA) the 16 plants species were ranked. The rank was created by (i) the correlation coefficients between the first flowering dates and the $\mathrm{T_{eff}}$ temperatures (Figure 5.5 and Figure 5.6), (ii) the temporal shifts (expressed in day/°C) of first flowering as a response to a unit change in $\mathrm{T_{eff}}$ (Figure 5.5), (iii) the relative response of first flowering to a relative change in ($\mathrm{T_{eff}}$). The negative value of slope (a) referred to the straightforward feature that higher mean temperature of previous periods of phenophase caused advanced flowering onset dates. These responses of the flowering onsets were species-specific and significant ($p < 0.05$; see Figure 5.5 and Figure 5.6).

Plants related to the same $\mathrm{T_{eff}}$ period were compared and ranked by the strength of the relation (r_0) between FO and $\mathrm{T_{eff}}$. Then the magnitude of the response to a unit change in $\mathrm{T_{eff}}$ (a) was considered. In Figure 5.5 the strongest relationships ($r_0 > 0.5$) of plants belong to different monthly and multi-monthly effective temperature periods are shown. The strongest correlation and the highest response to 1°C change in temperature were found in the following cases. Correlation coefficients (r_0) and slopes (a) in cases of the mean temperature of February (T_{FEB}), March (T_{MAR}), April (T_{APR}) and May (T_{MAY}) were considered. For T_{FEB} the highest reaction was shown by *T. farfara* ($r_0 = –0.68$; $a = –3.18$); for T_{MAR} by *S. fragilis* ($r_0 = –0.72$; $a = –2.75$) and *T. officinale* ($r_0 = -0.68$; $a = –3.56$); for T_{APR} by *S. vulgaris* ($r_0 = –0.77$; $a = –3.44$) and *V. vinifera* ($r_0 = –0.75$; $a = –4.01$); and for T_{MAY} by *R. pseudoacacia* ($r_0 = -0.56$; $a = -2.68$) as it is drawn in Figure 5.5.

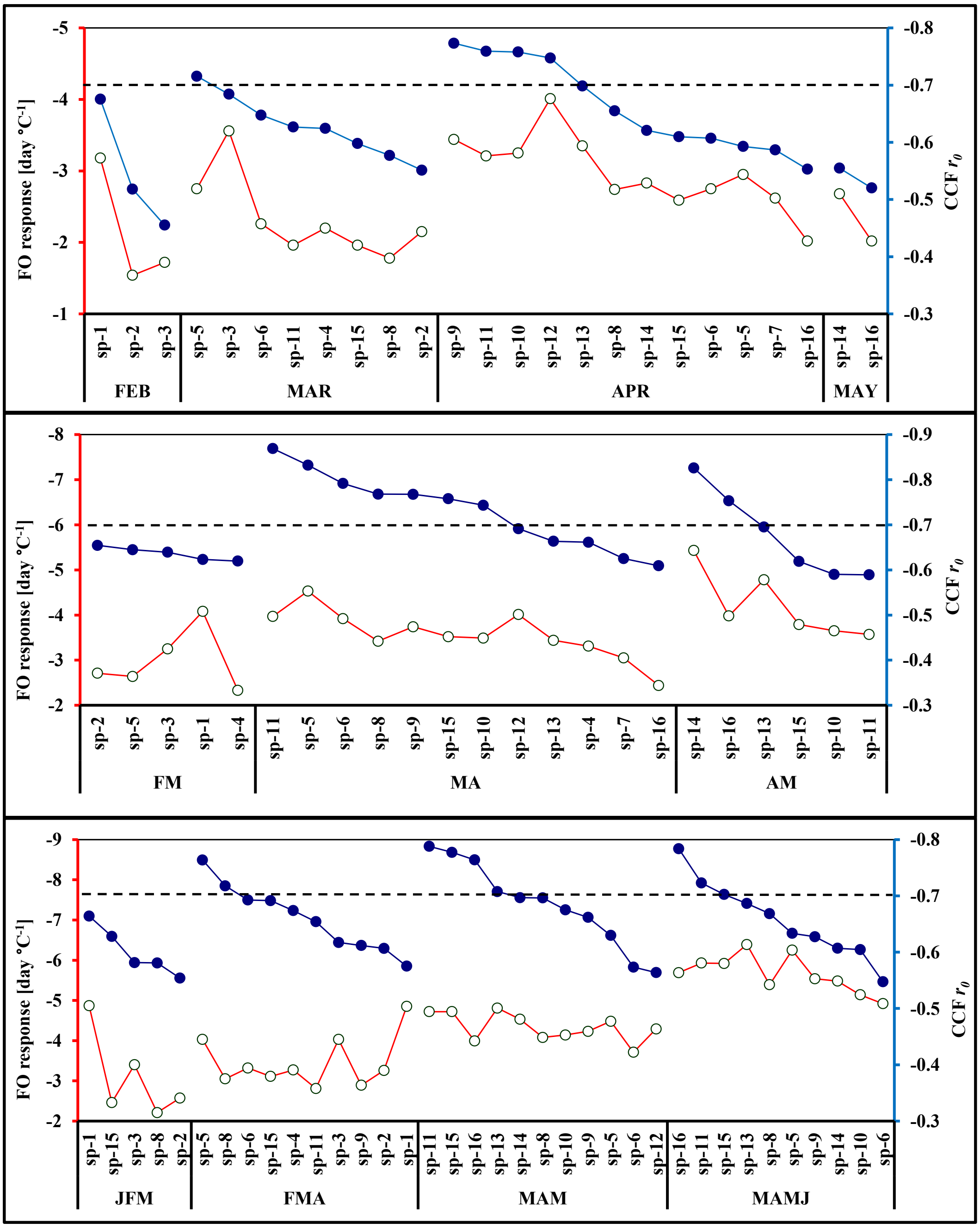


Figure 5.5: Rank of 16 plant species by significant ($p < 0.05$) correlations (vertical axis on the right, full symbols) and response of flowering onsets (expressed in the value of slopes originated from regression equations; vertical axis on the left, empty symbols) given to the mean temperatures of various time periods based on observations near Hermannstadt from 1851–1891. The straight dashed lines indicate the threshold of the strongest relations between the phenophase and the mean temperature.

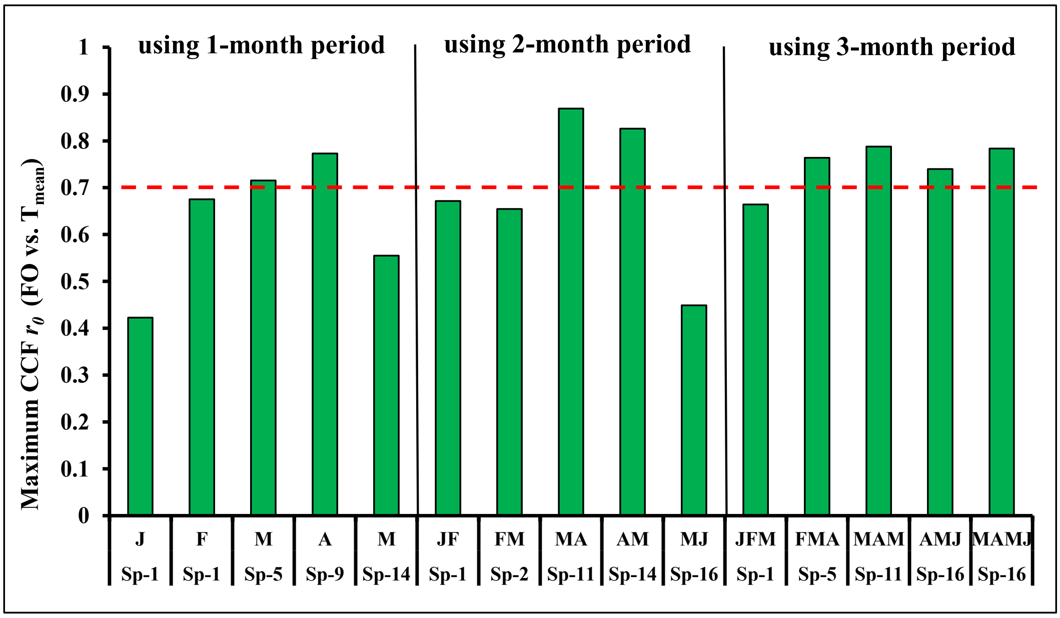


Figure 5.6: The highest significant CCF r_0 ($p<0.05$) values found by the moving window method between flowering onset (FO) and mean temperature (T_{mean}) for periods of different length based on observations near Hermannstadt, 1851–1891. The red straight dashed line indicates the threshold of the strongest relationships between the phenophase and the mean temperature.

In case of bi-monthly temperature means, for T_{FM} the relationships of the five earliest flowering plants were nearly the same (r_0 =–0.62–0.65), but in terms of the FO response, *T. farfara* seemed to be the most 'sensitive' (a =–4.08). T_{MA} influenced 12 plants effectively, in which case *E. europaeus* was at the first place of the ranked series. T_{AM} showed the strongest correlation with the late spring flowering plants, the highest response to 1°C change in temperature was expressed by *R. pseudoacacia* (r_0 =–0.83; a =–5.43).

In terms of the tri- and tetramonthly effective temperature periods in the ranked plant series belonging to T_{JFM}, the first was again *T. farfara* (r_0 =–0.66; a =–4.87) and a late spring plant, *S. nigra* (r_0 =–0.63; a =–2.46) occurred in the ranked series, too. The strongest relationship was detected and the highest reaction of FO was given to 1°C change in $\mathrm{T_{FMA}}$ by *S. fragilis* (r_0 =–0.76; a =–4.03); and in $\mathrm{T_{MAM}}$ by *E. europaeus* (r_0 =–0.79; a =–4.72) and *S. nigra* (r_0 =–0.78; a =–4.72). Finally, in case of the tetramonthly $\mathrm{T_{MAMJ}}$ *V. vinifera* (r_0 =–0.78; a =–5.69) showed the strongest relation between $\mathrm{T_{eff}}$ and FO.

Taking into consideration the FOs climatological utilization (e.g. as a proxy), the highest CCF r_0 values per period are shown for each monthly, multi-monthly 'time-window' in Figure 5.6. Interestingly, to all investigated time periods a total of 7 plants expressed the strongest response as 'thermal indicators'. These species (*T. farfara, S. bifolia, S. fragilis, S. vulgaris, E. europaeus, R. pseudoacacia, V. vinifera*) were mostly characterized by the highest FO responses as well.

In order to determine a rough but comparable indicator of heat sensitivity of FO, regression analyses were carried out on the time series of relative changes of FO and monthly, multi-monthly temperatures. Figure 5.7 is an illustration for the regression slope assessment of sensitivity using relative monthly temperature and flowering changes. From a geometric aspect, heat sensitivity is the higher, the regression line fits the better to the 45° line, namely to the theoretic, perfect phytothermometer. Thus, in the example of the Figure 5.7, *E. europaeus* (Sp-11) (a =–0.90; R^2 =0.69) responded more sensitively to 1°C change in mean temperature of MA period, than *F. vesca* (Sp-7) (a =–0.60; R^2 =0.39).

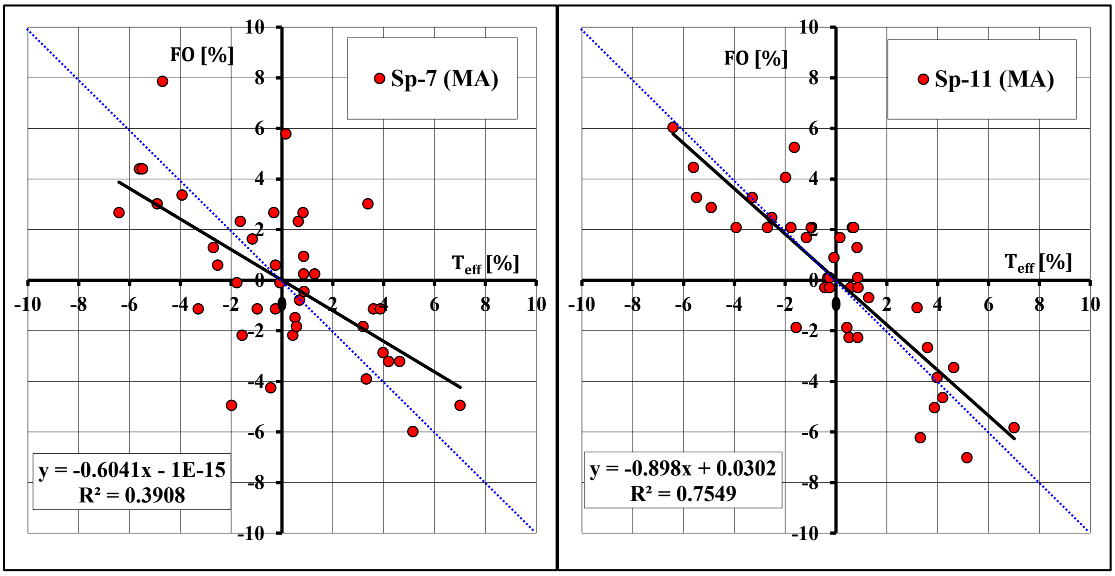


Figure 5.7: Example of regression slope assessment of heat sensitivity using relative bi-monthly effective temperature (T_{eff}) as explanatory variable and relative changes of flowering onset (FO) as dependent variable. In this way the plants are comparable as thermometers for the same period. (Sp-7: *F. vesca*; Sp-11: *E. europaeus*; MA=T_{eff} period; solid line=linear regression line; dotted line=line with $a = -1$ as a 45° slope).

Testing flowering onset as a proxy

The phenophase onset was tested as temperature proxy using datasets from Mediasch (Figure 5.8). Results of the regression analyses on temperature and phenological data of Hermannstadt were applied to estimate the effective temperature of 14 plant species observed at both places. According to the proxy-testing, the later the plant begins to flower, and the longer the period of effective temperature is (i.e. multi-monthly mean temperature was the most effective), the more accurate the estimation of T_{eff} by the FO.

In Figure 5.8 the four most accurate indicator plants are shown, which were selected by considering the previous results of heat sensitivity rankings. These were mostly late spring – early summer flowering species, namely *E. europaeus*

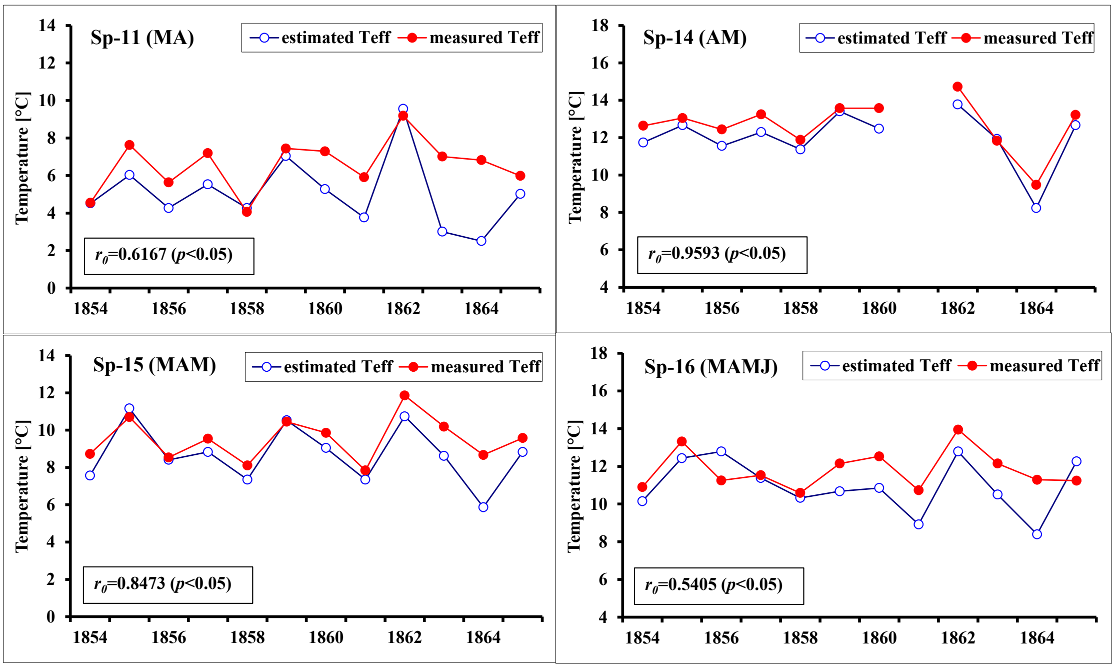


Figure 5.8: Four examples of testing the accuracy of the proxy by estimating the effective temperature (T_{eff}) from the flowering onset data of Mediasch based on the linear regression equations on temperature and phenological data of Hermannstadt in case of 14 plant species observed (1854–1865) at both places. (Sp-11: *E. europaeus*; Sp-14: *R. pseudoacacia*; Sp-15: *S. nigra*; Sp-16: *V. vinifera*; T_{eff} periods: MA, AM, MAM, MAMJ).

(Sp-11), *R. pseudoacacia* (Sp-14), *S. nigra* (Sp-15), and *V. vinifera* (Sp-16). In case of *R. pseudoacacia* the average difference between measured and estimated T_{eff} ($=T_{\mathrm{AM}}$) was 0.50 °C, and SD was 0.41 °C. For *S. nigra* concerning T_{MAM} the same values were 0.34 °C and 0.84 °C, respectively. Finally, in terms of *V. vinifera* these values appertain to T_{MAMJ} were found as 0.32 °C and 1.24 °C, respectively. In summary, FO data of the most sensitive heat indicator plants were applicable to estimate the T_{eff} data – as a first guess. The accuracy of estimation was between 1.0 °C and 1.5 °C.

5.4 Discussion

In the first part of this study the main characteristics of the flowering phenological and climatological time series, as well as their relationships were analysed. Our results are consistent with other studies (Auer *et al.*, 2001; Bohm *et al.*, 2001) found for climatological conditions in the second part of the 19th century, namely, the temperature time series did not contain any increasing or decreasing trend in this part of Europe. Based on our findings, the majority of plants are affected most strongly by the mean bi-monthly or tri-monthly temperatures prior to the date of flowering. In addition, several plants (such as the flowering onset of *Scilla bifolia*) were also influenced by the heat conditions in late summer – autumn of the previous year, as similar conclusion was drawn by Gordo and Sanz (2010) for the Mediterranean region.

The main aim of this study was to analyse the species-specific heat-sensitivity of flowering onset characteristics of different plant species. Only few studies (see, e.g., Root *et al.*, 2005; Aono and Kazui, 2008; Rutishauser *et al.*, 2009) focused on this topic using this perspective so far. According to studies of 20th century' data, major synchronous break was found in phenological time series during the 1980s in Europe (Dose and Menzel, 2004; Schleip *et al.*, 2006). Furthermore, significant earlier shift in flowering onset dates (1952–2000) of *Taraxacum officinale*, *Sambucus nigra*, as well as in case of the *Robinia pseudoacacia* (1951–1994) were shown by Szabó *et al.* (2016) and Walkovszky (1998) among our examined species. In contrary their findings in the neighbourhood country, Hungary, we did not find linear trend in the flowering onset data – probably because our data were recorded during the 19th century, when the impacts of human induced climatic changes were not yet as influential as in the late 20$^{\text{th}}$ century.

Our central addressed issue of testing flowering onset as proxy variable for temperature was based on our heat sensitivity results. According to the validation tests on data from Mediasch, the flowering onsets of *Robinia pseudoacacia* and *Vitis vinifera* proved to be the most accurate phyto-thermometers. Hence, these two species can be utilized to provide data with highest confidence as proxy for estimating the mean temperature of their effective temperature periods (*Robinia pseudoacacia* – April-May; *Vitis vinifera* – March-April-May-June) in the examined time period and region. Overall, we could estimate effective temperature of 14 plant species with 1–1.5 °C accuracy. Taking into account the general climatological differences of the two sites (Mediasch is warmer in yearly average by 1.04 °C compared to Hermannstadt), the average bias of proxy estimations could be slightly reduced by applying a simple additive correction. Therefore, this method in first approach is appropriate as a robust estimation of mean temperature from flowering data. The estimation is robust, which originates from the uncertainty of geographical factors, which can explain the spatial variance of flowering dates (Wang *et al.*, 2015). Furthermore, this uncertainty also comes from the rough resolution of the temperature records, since the monthly and multi-monthly averages of temperature time-series are good representatives of the spring heat conditions, but not as accurate as if the effective temperatures were obtained based on daily data (e.g. degree-day calculation; see Schwartz (2013)). If more detailed data series (either temporally or spatially) are available, the method can be refined to result in a more accurate estimation, which is of interest in order to better understand past climates of periods or locations where no instrumental records are available.

CHAPTER 6

Is citizen science the recipe for the survival of paper-based phenological networks in Europe?[*]

Viewpoint

Prior to the late nineteenth century, nearly all scientific research was conducted by unpaid amateurs. Members of the public have long investigated scientific questions or recorded observations about nature (Miller-Rushing *et al.*, 2012). Farmers, hunters, and amateur naturalists often kept records of phenological events. Grape harvest dates, for instance, were recorded in Austria since the sixteenth century (Maurer *et al.*, 2009) at monasteries, and court diarists noted the flowering dates of cherry blossoms in Japan for over 1200 years (Primack *et al.*, 2000). The cul-

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[*] The paper co-authored with Helfried Scheifinger (Scheifinger and Templ, 2016) is published in *BioScience*.

ture of science changed during the nineteenth century, and science became almost exclusively an activity of professional scientists. Nevertheless, the contribution of citizen science (CS) – based publications to various fields of research has been steadily increasing in recent years. This contribution fills niches that tackle ecological questions at scales that would be unachievable through professional science alone (Miller-Rushing *et al.*, 2012; Tulloch *et al.*, 2013). Such activity was termed *citizen science* in the 1990s by researchers at the Cornell Laboratory of Ornithology and refers to the engagement of nonprofessionals in scientific investigations. Recently, hundreds of CS projects have proliferated in various scientific disciplines.

Phenology – the timing of seasonal activities of living organisms – is perhaps the simplest method for tracking the response of species to environmental change. Examples of phenological occurrences include the first flight of butterflies or the first appearance of migratory birds – or the date of the emergence of the leaves and flowers of plants. Plant phenological observations have traditionally been collected in Europe by a network of volunteer observers operated by national meteorological and hydrometeorological services (NMHS). The report of the European Cooperation in Science and Technology (COST) Action 725 summarizes the available information about national phenological networks in Europe (Nekovár *et al.*, 2008).

Phenological data collection, with its rather small data volume, has often run unobtrusively alongside mainstream meteorological data collection and has therefore survived in many NMHSs despite the ups and downs of interest in phenological science over time. An advantage of NMHSs is their experience in running station networks, controlling the quality of incoming data, and digitizing and storing those data on appropriate devices. Traditional phenological data collection has always relied on volunteer observers, who were willing to regularly visit their selected plants and places, working with pencil and paper, filling in and sending observational sheets to their national weather service. Such data collection has been challenged by a number of unknown sociological factors, which together caused a dramatic drop of phenological observations in recent decades in Europe (Nekovár *et al.*, 2008).

However, the recent development of personal electronic devices has great potential to for increasing the stream of phenological observations. This technology already facilitates CS ecological data collection enormously, such as through mobile applications, social media, education programs, webcams, and even drones.

At the Zentralanstalt für Meteorologie und Geodynamik (ZAMG), the Austrian national meteorological service, we have decided to add new CS technologies to our traditional paper-based phenological data collection. Since 2006, our Web interface has contributed about 50 percent of our phenological observations, although we do not know the percentage of new observers, how many started contributing with the Web interface, or how many traditional observers made the switch from paper. Within the next few months, our PhenoWatch app, which has been developed within CS projects related to schools, will become accessible to the public and help resolve these questions.

If one compares the USA National Phenology Network (USA–NPN) with traditional European phenological observation programs , one finds that it is very young, has always relied on state-of-the-art electronic media, has comparatively large financial support, and has a much broader scope (more than 300 animal and 800 plant species) and therefore a higher added value for a number of ecological questions (Rosemartin *et al.*, 2014). The traditional European programs appear more limited in scope, for historical reasons: They are usually sited within NMHSs, which are *per se* not ecological institutions, although phenology is of interest to climatologists who study the impact of atmospheric variability on plants and animals. The USA-NPN is an organization employing a staff of about 15.

In Europe, most of the phenological networks are run by the NMHSs, involving only one or two people, who have limited time to spend on the comparably narrow and restricted programs. The size and scope of the USA-NPN could extend far beyond what NMHSs could ever provide, but it will need to secure continuous financing, whereas predominantly government-financed NMHSs offer established infrastructure and promise continuous operation over decades.

What does the future hold for European phenology? On one hand, we definitely need a continuation of phenological data collection within standard networks. On the other hand, most NMHSs in Europe have experienced problems from either dwindling numbers of traditional observers or simply being shut down because of a lack of interest. One might wonder whether new CS technologies can help solve these problems. And even if they secure or even extend the traditional European phenological networks, the question remains: In which way could these new CS technologies be implemented in the NMHS observational systems?

The first area to address concerns phenological data collection procedures. Here, we see the following options for the NMHSs phenological networks: (a) Continue to maintain phenological observations with the traditional observer sheet programs, which bears the risk of dying out because of dwindling observer numbers. (b) Continue to maintain phenological observations with the traditional observer sheet program but extend it with new CS technologies. In this model, the – old – phenological time series are continued by the traditional observers. The risk of a collapse of the network might be avoided, and at some later date, the new CS technologies will have replaced traditional phenological data collection completely.

The second issue is that new CS technologies facilitate data collection such that the range of species and phases can easily be extended indefinitely. Is there any benefit to extending the range of species and phase observations? Possible approaches include the following: (a) Continue with the traditional set of plants, animals, and phenophases but extend their range with the new CS technology. This bears the risk of proliferation, when an NMHS tries to handle data with a too-large ecological scope. (b) Transfer ecological data collection to a specialized institute, as Bonney *et al.* (2014) have mentioned, by creating *centers for citizen science* that coordinate and synthesize the whole process from research hypothesis to data evaluation. This would be the ideal case, but here, we see funding risks and other problems associated with building such infrastructure from scratch.

The third aspect concerns the value of international data collection efforts: (a) PEP725 (`www.pep725.eu`) is a good initiative, but it is so far restricted to the *a posteriori* fusion of phenological data from national NMHS phenological programs.

New CS technologies can easily be adjusted to international applicability. Just as the International Phenological Gardens of Europe and the GLOBE program have standard observation guides, collection of phenological observations with CS methods could also adhere to a common standard in Europe. Therefore, the individual countries could recruit their citizens, but the observations would be carried out on the basis of an internationally coordinated scheme.

A possible vision for the future of the European NMHS phenological networks could encompass the implementation of CS methods through an internationally coordinated program at the NMHSs of each country. The European Citizen Science Association could play a major role in the coordination of such a program.

Summary

Phenology is the study of periodically recurring life-cycle events (phenophases) of living organisms'. A growing number of studies call attention to the ecological impacts of climate change, including shifts in phenology. Changes in phenological patterns have major implications on many sectors, including agriculture (e.g. appearance of pests), health (e.g. allergy season) and climate change research (e.g. biological indicators).

This PhD thesis consists of studies from several major fields of phenological research in order (i) to understand spatial and temporal patterns of flowering phenology in Europe, (ii) to improve predictions of phenological events, (iii) to utilize phenological data for reconstruction of paleoclimate and (iv) to call attention to a particular option of phenological data collection.

One of the major aims of the research was to discover phenological patterns of flowering. It is shown that negative (timing of flowering gradually shifting earlier) phenological trends can be detected over the last few decades in Hungary (Chapter 2) and in many regions of northern and eastern Central Europe (Chapter 3). The influence of various direct (temperature, precipitation) and indirect (North Atlantic Oscillation) climate variables was identified due to these spatio-temporal trends. As a methodological development, a specialized statistical method was applied to plant phenological data. It was demonstrated that Cox proportional hazards models have a stronger predictive power in phenological research than traditional regression models (Chapter 4). It is known that phenological data can be effectively utilized for paleoclimate reconstruction. Additionally, a method which is appropriate to estimate past heat conditions with an accuracy of 1–1.5°C was introduced (Chapter 5). And finally, an outlook on the future of phenological networks involving volunteers in data collection (*citizen science*) in Europe is given in Chapter 6.

Összefoglalás

A fenológia, az élőlények életmenetében ciklikusan bekövetkező, évenként visszatérő jelenségeket (fenofázisok) vizsgáló tudományterület. Egyre növekvő számú tanulmány hívja fel a figyelmet az éghajlatváltozás ökológiai hatásaira, ideértve a fenofázisok eltolódásait. Ezzel összefüggésben, a fenológiai mintázatokban fellépő változásoknak jelentős szerepe van a mezőgazdaságban (pl. kártevők megjelenése), az egészségügyben (pl. allergia szezon), valamint a klímaváltozás kutatásban (pl. biológiai indikátorok).

E doktori értekezés több tanulmányt tartalmaz a fenológiai kutatás főbb területeiről annak érdekében, hogy (i) megértsük a virágzás-fenológia tér- és időbeli mintazátait Európában, (ii) továbbfejlesszük a fenológiai események előrejelzését, (iii) paleoéghajlati rekonstrukciókat állítsunk elő fenológiai adatok alapján, valamint (iv) felhívjuk a figyelmet a fenológiai adatgyűjtés új lehetőségeire.

Kutatásaim egyik legfontosabb célja a virágzás-fenológiai mintázatok feltárása volt. Azt tapasztaltuk, hogy Magyarországon (2. fejezet) és Európa számos régiójában (3. fejezet) negatív fenológiai trendek (azaz a növények korábban lépnek az egyes egyedfejlődés virágzási stádiumába) figyelhetőek meg. Direkt (hőmérséklet, csapadék) és indirekt (Észak Atlanti Oszcilláció) klíma változókat azonosítottam, melyek e tér- és időbeli trendekért felelősek. Módszertani fejlesztésként egy, a növény-fenológiai elemzések eszköztára számára eddig nem ismert statisztikai módszert alkalmaztunk. Kimutattuk (4. fejezet), hogy a Cox-féle arányos kockázati modellek (proportional hazards models) előrejelző ereje nagyobb, mint a regressziós modelleknek. Ismert, hogy a virágzás-fenológiai adatok alkalmasak éghajlati rekonstrukcióra. Bemutattunk egy módszert (5. fejezet), mely lehetőve teszi a múltbeli hőviszonyok 1–1.5 °C pontosságú becslését. S végül kitekintést adtunk a széles társadalmi részvételen (*citizen science*) alapuló fenológiai megfigyelések, megfigyelőhálózatok jövőjéről Európában (6. fejezet).

Bibliography

Abdi H (2007). "Bonferroni and Sidăk corrections for multiple comparisons." In N Salkind (ed.), *Encyclopedia of measurement and statistics*. Thousand Oaks, CA: Sage.

Aguilera F, Fornaciari M, Ruiz-Valenzuela L, Galán C, Msallem M, Dhiab AB, Diaz-de la Guardia C, del Mar Trigo M, Bonofiglio T, Orlandi F (2015). "Phenological models to predict the main flowering phases of olive (*Olea europaea* L.) along a latitudinal and longitudinal gradient across the Mediterranean region." *International Journal of Biometeorology*, **59**, 629–641.

Ahas R, Aasa A (2006). "The effects of climate change on the phenology of selected Estonian plant, bird and fish populations." *International Journal of Biometeorology*, **51**, 17–26.

Anderson J, Inouye D, McKinney A, Colautti R, Mitchell-Olds T (2012). "Phenotypic plasticity and adaptive evolution contribute to advancing flowering phenology in response to climate change." *Proceedings of the Royal Society B: Biological Sciences*, **279**, 3843–3852.

Aono Y, Kazui K (2008). "Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to reconstruction of springtime temperatures since the 9th century." *International Journal of Climatology*, **28**, 905–914.

Askeyev OV, Sparks TH, Askeyev IV, Tishin DV, Tryjanowski P (2010). "East versus West: contrasts in phenological patterns?" *Global Ecology and Biogeography*, **19**, 783–793.

Auer I, Bohm R, Jurkovic A, Lipa W, Orlik A, Potzmann R, Schoener W, Ungersbueck M, Matulla C, Briffa K, Jones P, Efthymiadis D, Brunetti M, Nanni T, Maugeri M, Mercalli L, Mestre O, Moisselin JM, Begert M, Mueller-Westermeier G, Kveton V, Bochnicek O, Stastny P, Lapin M, Szalai S, Szentimrey T, Cegnar T, Dolinar M, Gajic-Capka M, Zaninovic K, Majstorovic Z, Nieplova E (2007). "HISTALP – historical instrumental climatological surface time series of the Greater Alpine Region." *International Journal of Climatology*, **27**, 17–46.

Auer I, Bohm R, Schoner W (2001). *Austrian long-term climate 1767–2000 – Multiple instrumental climate time series from Central Europe.* Zentralanstalt fur Meteorologie und Geodynamik, Wien.

Badeck FW, Bondeau A, Bottcher K, Doktor D, Lucht W, Schaber J, Sitch S (2004). “Responses of spring phenology to climate change.” *New Phytologist*, **162**, 295–309.

Bartholy J, Pongrácz R, Gelybó G (2009a). “Climate signals of the North Atlantic Oscillation detected in the Carpathian Basin.” *Applied Ecology and Environmental Research*, **7**, 229–240.

Bartholy J, Pongrácz R, Nagy J, Pieczka I, Hufnágel L (2012). “Regional climate change impacts on wild animals’ living territory in Central Europe.” *Applied Ecology and Environmental Research*, **10**, 107–120.

Bartholy J, Pongrácz R, Torma C, Pieczka I, Kardos P, Hunyady A (2009b). “Analysis of regional climate change modelling experiments for the Carpathian Basin.” *International Journal of Global Warming*, **1**, 238–252.

Bartomeus I, Ascher J, Wagner D, Danforth B, Colla S, Kornbluth S, Winfree R (2011). “Climate-associated phenological advances in bee pollinators and bee-pollinated plants.” *Proceedings of the National Academy of Sciences*, **108**, 20645–20649.

Bauer S, Gienapp P, Madsen J (2004). “The relevance of environmental conditions for departure decision changes en route in migrating geese.” *Ecology*, **89**, 1953–1960.

Beebee TJC (2002). “Amphibian phenology and climate change.” *Conservation Biology*, **16**, 1454–1454.

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012). “Impacts of climate change on the future of biodiversity.” *Ecology Letters*, **15**, 365–377.

Bertin R (2008). “Plant phenology and distribution in relation to recent climate change.” *Journal of the Torrey Botanical Society*, **135**, 126–146.

Bewick V, Cheek L, Ball J (2004). “Statistics review 12: survival analysis.” *Critical Care*, **8**, 389–394.

Bohm R, Auer I, Brunetti M, Maugeri M, Nanni T, Schoener W (2001). “Regional temperature variability in the European Alps: 1760–1998 from homogenized instrumental time series.” *International Journal of Climatology*, **21**, 1779–1801.

Bonney R, Cooper C, Dickinson J, Kelling S, Phillips T, Rosenberg K, Shirk J (2009). “Citizen science: a developing tool for expanding science knowledge and scientific literacy.” *BioScience*, **59**, 977–984.

Bonney RI, Phillips TB, Wiggins A, Ballard HL, Miller-Rushing AJ, Parrish JK (2014). “Next steps for citizen science.” *Science*, **343**, 1436–1437.

Both C, van Asch M, Bijlsma RG, van den Burg AB, Visser ME (2009). “Climate change and unequal phenological changes across four trophic levels: constraints or adaptations?” *Journal of Animal Ecology*, **78**, 73–83.

Bradshaw W, Holzapfel C (2008). “Genetic response to rapid climate change: it’s seasonal timing that matters.” *Molecular Ecology*, **17**, 157–166.

Bruns E, Chmielewski F, van Vliet A (2003). “The global phenological monitoring concept.” In M Schwartz (ed.), *Phenology: An Integrative Environmental Science*. Springer Netherlands.

Buermann W, Anderson B, Dickinson R, Lucht W, Potter C, Myneni R (2003). “Interannual covariability in Northern Hemisphere air temperatures and greenness associated with El Niño–Southern Oscillation and the Arctic Oscillation.” *Journal of Geophysical Research*, **108**, 4396.

Burrows M, Schoeman D, Buckley L, Moore P, Poloczanska E, Brander K, Brown C, Bruno J, Duarte C, Halpern B, Holding J, Kappel C, Kiessling W, O’Connor M, Pandolfi J, Parmesan C, Schwing F, Sydeman W, Richardson A (2011). “The pace of shifting climate in marine and terrestrial ecosystems.” *Science*, **334**, 652–655.

Buse A, Dury SJ, Woodburn RJW, Perrins CM, Good JEG (1999). “Effects of elevated temperature on multi-species interactions: the case of Pedunculate Oak, Winter Moth and Tits.” *Functional Ecology*, **13**, 74–82.

Chambers LE, Altwegg R, Barbraud C, Barnard P, Beaumont LJ, Crawford RJM, Durant JM, Hughes L, Keatley MR, Low M, Morellato PC, Poloczanska ES, Ruoppolo V, Vanstreels RET, Woehler EJ, Wolfaardt AC (2013). “Phenological changes in the Southern Hemisphere.” *PLoS ONE*, **8**, e75514.

Chen I, Hill JK, Ohlemüller R, Roy DB, Thomas CD (2011). “Rapid range shifts of species associated with high levels of climate warming.” *Science*, **333**, 1024–1026.

Chmielewski F (2013). “Phenology in agriculture and horticulture.” In M Schwartz (ed.), *Phenology: An Integrative Environmental Science*. Springer Netherlands.

Chmielewski F, Heider S, Moryson S, Bruns E (2013). "International phenological observation networks: concept of IPG and GPM." In M Schwartz (ed.), *Phenology: An Integrative Environmental Science*. Springer Netherlands.

Chmielewski FM, Rotzer T (2001). "Response of tree phenology to climate change across Europe." *Agricultural and Forest Meteorology*, **108**, 101–112.

Chmielewski FM, Rotzer T (2002). "Annual and spatial variability of the beginning of growing season in Europe in relation to air temperature changes." *Climate Research*, **19**, 257–264.

Chuine I (2010). "Why does phenology drive species distribution?" *Philosophical Transactions of the Royal Society, B: Biological Sciences*, **365**, 3149–3160.

Cleland E, Allen J, Crimmins T, Dunne J, Pau S, Travers S, Zavaleta E, Wolkovich E (2012). "Phenological tracking enables positive species responses to climate change." *Ecology*, **93**, 1765–1771.

Cleland E, Chuine I, Menzel A, Mooney HA, Schwartz MD (2007). "Shifting plant phenology in response to global change." *Trends in Ecology and Evolution*, **22**, 357 – 365.

Cleveland W (1979). "Robust locally weighted regression and smoothing scatterplots." *Journal of American Statistical Association*, **74**, 829 – 836.

Cook B, Terano A, Steiner A (2010). "Ecological forecasting under climatic data uncertainty: a case study in phenological modeling." *Environmental Research Letters*, **5**, 044014.

Cook BI, Wolkovich EM, Parmesan C (2012). "Divergent responses to spring and winter warming drive community level flowering trends." *Proceedings of the National Academy of Sciences*, **109**, 9000–9005.

Cortazar-Atauri I, Brisson N, JP G (2009). "Performance of several models for predicting budburst date of grapevine (*Vitis vinifera L.*)." *International Journal of Biometeorology*, **53**, 317–326.

Cox DR (1972). "Regression models and life-tables." *Journal of the Royal Statistical Society, Series B*, **34**, 187–220.

Cramer W, Yohe G, Auffhammer M, Huggel C, Molau U, Dias M, Solow A, Stone D, Tibig L (2014). "Detection and attribution of observed impacts." In C Field, V Barros, D Dokken, K Mach, M Mastrandrea, T Bilir, M Chatterjee, K Ebi, Y Estrada, R Genova, B Girma, E Kissel, A Levy, S MacCracken, P Mastrandrea, L White (eds.), *Climate change 2014: Impacts, adaptation and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Craufurd P, Wheeler T (2009). "Climate change and the flowering time of annual crops." *Journal of Experimental Botany*, **60**, 2529–2539.

Crepinsek Z, Zrnec C, Susnik A, Zust A (2008). "Slovenian phenological observations." In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe.* COST Office, Brussels.

Crimmins T, Crimmins MA, Bertelsen D (2010). "Complex responses to climate drivers in onset of spring flowering across a semi-arid elevation gradient." *Journal of Ecology*, **98**, 1042–1051.

Csecserits A, Czúcz B (2008). "Az éghajlatváltozás lappangó hatásai: növényfenológiai adatforrások Magyarországon (in Hungarian)." In *Research Abstracts of the KÖSZI 2008: Életre keltett adatok, 3. Kvantitatív Ökológiai Szimpózium (Budapest, Hungary)*, p. 30.

Dawson T, Jackson S, House J, Prentice I, Mace G (2011). "Beyond predictions: biodiversity conservation in a changing climate." *Science*, **332**, 53–58.

DeCesare N, Hebblewhite M, Bradley M, Hervieux D, Neufeld L, Musiani M (2014). "Linking habitat selection and predation risk to spatial variation in survival." *Journal of Animal Ecology*, **83**, 343–352.

Defila C, Clot B (2001). "Phyto-phenological trends in Switzerland." *International Journal of Biometeorology*, **45**, 203–207.

Demarée G, Rutishauser T (2011). "From periodical observations to anthochronology and phenology: the scientific debate between Adolphe Quetelet and Charles Morren on the origin of the word phenology." *International Journal of Biometeorology*, **55**, 753–761.

Demarée GR, Rutishauser T (2009). "Origins of the word Phenology." *EOS, Transactions American Geophysical Union*, **90**, 291–291.

Dickinson J, Bonney R (2012). *Citizen science: public participation in environmental research.* Comstock Publishing Associates, Ithaca, NYC. ISBN 978-0-8014-4911-6.

Dickinson JL, Shirk J, Bonter D, Bonney R, Crain R, Martin J, Phillips T, Purcell K (2012). “The current state of citizen science as a tool for ecological research and public engagement.” *Frontiers in Ecology and the Environment*, **10**, 291–297.

Dickinson JL, Zuckerberg B, Bonter DN (2010). “Citizen science as an ecological research tool: challenges and benefits.” *Annual Review of Ecology, Evolution and Systematics*, **41**, 149–172.

Diez J, Ibanez I, Miller-Rushing A, Mazer S, Crimmins T, Crimmins M, Bertelsen C, Inouye D (2012). “Forecasting phenology: from species variability to community patterns.” *Ecology Letters*, **15**, 545–553.

Donnelly A, Jones M, Sweeney J (2004). “A review of indicators of climate change for use in Ireland.” *International Journal of Biometeorology*, **49**, 1–12.

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

Dövényi Z (2010). *Magyarország kistájainak katasztere (in Hungarian)*. MTA FKI, Budapest.

Dunay S (1984). “Növényfenológiai megfigyelések Magyarországon (in Hungarian).” *Légkör*, **29**, 2–9.

Duputie A, Rutschmann A, Ronce O, Chuine I (2015). “Phenological plasticity will not help all species adapt to climate change.” *Global Change Biology*, **21**, 3062–3073.

Elzinga JA, Atlan A, Biere A, Gigord L, Weis AE, Bernasconi G (2007). “Time after time: flowering phenology and biotic interactions.” *Trends in Ecology and Evolution*, **22**, 432–439.

Estes JA, Terborgh J, Brashares JS, Power ME, Berger J, Bond WJ, Carpenter SR, Essington TE, Holt RD, Jackson JBC, Marquis RJ, Oksanen L, Oksanen T, Paine R, Pikitch EK, Ripple WJ, Sandin SA, Scheffer M, Schoener TW, Shurin JB, Sinclair ARE, Soule ME, Virtanen R, Wardle DA (2011). “Trophic downgrading of planet Earth.” *Science*, **333**, 301–306.

Estrella N, Sparks T, Menzel A (2009). “Effects of temperature, phase type and timing, location, and human density on plant phenological responses in Europe.” *Climate Research*, **39**, 235–248.

ETCBD (2006). “The indicative map of European biogeographical regions: methodology and development.” *Technical report*, European Topic Centre on Biological Diversity (ETCBD), National Museum of Natural History, France.

Field C, Barros V, Dokken D, Mach K, Mastrandrea M, Bilir T, Chatterjee M, Ebi K, Estrada Y, Genova R, Girma B, Kissel E, Levy A, MacCracken S, Mastrandrea P, White L (eds.) (2014). *Climate change 2014: Impacts, adaptation and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York.

Fitchett J, Grab S, Thompson D (2015). “Plant phenology and climate change: progress in methodological approaches and application.” *Progress in Physical Geography*, **39**, 460–482.

Fitter A, Fitter RSR (2002). “Rapid changes in flowering time in British plants.” *Science*, **296**, 1689–1691.

Fitter AH, Fitter RSR, Harris ITB, Williamson MH (1995). “Relationships between first flowering date and temperature in the flora of a locality in central England.” *Functional Ecology*, **9**, 55–60.

Forrest J, Miller-Rushing A (2010). “Toward a synthetic understanding of the role of phenology in ecology and evolution.” *Philosophical Transactions of the Royal Society, B: Biological Sciences*, **365**, 3101–3112.

Franklin J, Serra-Diaz J, Syphard A, Regan H (2016). “Global change and terrestrial plant community dynamics.” *Proceedings of the National Academy of Sciences*, **113**, 3725–3734.

Franks S (2015). “The unique and multifaceted importance of the timing of flowering.” *American Journal of Botany*, **102**, 1041–1402.

Frund J, Dormann C, Tscharntke T (2011). “Linne’s floral clock is slow without pollinators – flower closure and plant-pollinator interaction webs.” *Ecology Letters*, **14**, 896–904.

Fu Y, Piao S, de Beeck M, Cong N, Zhao H, Zhang Y, Menzel A, Janssens I (2014). “Recent spring phenology shifts in western Central Europe based on multiscale observations.” *Global Ecology and Biogeography*, **23**, 1255–1263.

Garcia-Mozo H, Galan C, Belmonte J, Bermejo D, Candaud P, Diaz de la Guardiae C, Elvira B, Gutierrez M, Jato V, Silva I, Trigo M, Valencia R, Chunie I (2009).

"Predicting the start and peak dates of the *Poaceae* pollen season in Spain using process-based models." *Agricultural and Forest Meteorology*, **149**, 256–262.

Ge Q, Wang H, Rutishauser T, Dai J (2015). "Phenological response to climate change in China: a meta-analysis." *Global Change Biology*, **21**, 265–274.

Gezon G, Inouye D, Irwin R (2016). "Phenological change in a spring ephemeral: implications for pollination and plant reproduction." *Global Change Biology*, **22**, 1779–1793.

Gienapp P, Hemerik L, Visser M (2005). "A new statistical tool to predict phenology under climate change scenarios." *Global Change Biology*, **11**, 600–606.

Gienapp P, Hemerik L, Visser M (2010). "Latitudinal variation in breeding time reaction norms in a passerine bird." *Journal of Animal Ecology*, **79**, 836–842.

Gienapp P, Reed T, Visser M (2014). "Why climate change will invariably alter selection pressures on phenology." *Philosophical Transactions of the Royal Society, B: Biological Sciences*, **281**, 20141611.

Gienapp P, Teplitsky C, Alho J, Mills J, Merila J (2008). "Climate change and evolution: disentangling environmental and genetic responses." *Molecular Ecology*, **17**, 167–178.

Gobiet A, Kotlarski K, Beniston M, Heinrich G, Rajczak J, Stoffel M (2014). "21st century climate change in the European Alps: a review." *Science of The Total Environment*, **493**, 1138–1151.

Gordo O (2007). "Why are bird migration dates shifting? A review of weather and climate effects on avian migratory phenology." *Climate Research*, **35**, 37–58.

Gordo O, Sanz JJ (2010). "Impact of climate change on plant phenology in Mediterranean ecosystems." *Global Change Biology*, **16**, 1082–1106.

Grisule G, Briede A (2008). "The history and current status of phenological recording in Latvia." In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe*. COST Office, Brussels.

Gupta R, Reybroeck W, van Veen J, Gupta A (2014). *Beekeeping for poverty alleviation and livelihood security: Vol. 1. Technological aspects of beekeeping.* Springer Netherlands. ISBN 978-94-017-9198-4.

Haan CT (2002). *Statistical methods in hydrology.* Iowa State University Press, Ames, Iowa. ISBN 978-0-813-81503-9.

Hannah L (2010). *Climate change biology*. Elsevier, Amsterdam, The Netherlands. ISBN 978-0-123-74182-0.

Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M (2008). "A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006." *Journal of Geophysical Research: Atmospheres*, **113**, D20119.

Herms D (2004). "Using degree-days and plant phenology to predict pest activity." In V Krischik, J Davidson (eds.), *IPM (Integrated Pest Management) of Midwest Landscapes*. Minnesota Agricultural Experiment Station Publication.

Hodges T (1990). *Predicting crop phenology*. CRC Press. ISBN 978-0-849-36745-8.

Hodžič S, Voljevica N (2008). "Phenology in Bosnia and Hercegovina." In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe*. COST Office, Brussels.

Hofmann G, Todgham A (2010). "Living in the now: physiological mechanisms to tolerate a rapidly changing environment." *Annual Review of Physiology*, **72**, 127–145.

Hofstra N, Haylock M, New M, Jones P (2009). "Testing E–OBS European high-resolution gridded data set of daily precipitation and surface temperature." *Journal of Geophysical Research*, **114**, D21101.

Holopainen J, Helama S, Timonen M (2006). "Plant phenological data and tree–rings as paleoclimate indicators in south–west Finland since AD 1750." *International Journal of Biometeorology*, **51**, 61–72.

Hughes L (2000). "Biological consequences of global warming: is the signal already." *Trends in Ecology and Evolution*, **15**, 56–61.

Hurrel JW (1995). "Decadal trends in the North Atlantic Oscillation regional temperatures and precipitation." *Science*, **269**, 676–679.

Hurrel JW, van Loon H (1997). "Decadal variations in climate associated with the North Atlantic Oscillation." *Climatic Change*, **36**, 301–326.

Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (2003). "An overview of the North Atlantic Oscillation – The North Atlantic Oscillation: climate significance and environmental impact." *Geophysical Monograph Series*, **134**, 1–35.

Isépy I, Szabó I (2011). "In memoriam Dr. Priszter Szaniszló." *Botanikai Közlemények*, **98**, 1–20.

Jatczak K, Walawender J (2009). "Average rate of phenological changes in Poland according to climatic changes – evaluation and mapping." *Advances in Science and Research*, **3**, 127–131.

Jentsch A, Kreyling J, Boettcher-Treschkow J, Beierkuhnlein C (2009). "Beyond gradual warming: extreme weather events alter flower phenology of European grassland and heath species." *Global Change Biology*, **15**, 837–849.

Jiguet F, Gregory RD, DeVictor V, Green R, Vorisek P, Strien A, Couvet D (2010). "Population trends of European common birds are predicted by characteristics of their climatic niche." *Global Change Biology*, **16**, 497–505.

Johansson J, Kristensen N, Nilsson J, Jonzen N (2015). "The eco-evolutionary consequences of interspecific phenological asynchrony – a theoretical perspective." *Oikos*, **124**, 102–112.

Johnson JB, Omland K (2004). "Model selection in ecology and evolution." *Trends in Ecology and Evolution*, **19**, 101–108.

Jones P, Briffa K, Barnett T, Tett S (1988). "High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures." *The Holocene*, **8**, 455–471.

Jong R, Bruin S (2012). "Linear trends in seasonal vegetation time series and the modifiable temporal unit problem." *Biogeosciences*, **9**, 71–77.

Kalváne G, Romanovskaja D, Briede A, Baksiene E (2009). "Influence of climate change on phenological phases in Latvia and Lithuania." *Climate Research*, **39**, 209–210.

Kaplan EL, Meier P (1958). "Nonparametric estimation from incomplete observations." *Journal of the American Statistical Association*, **53**, 457–481.

Karyieva J, van Leeuven W, Woodhouse C (2012). "Impacts of climate gradients on the vegetation phenology of major land use types in Central Asia (1981–2008)." *Frontiers of Earth Science*, **6**, 206–225.

Kauserud H, Heegaard E, Semenov M, Boddy L, Halvorsen R, Stige L, Sparks T, Gange A, Stenseth N (2010). "Climate change and spring-fruiting fungi." *Proceedings of the Royal Society Biology*, **277**, 1169–1177.

Keresztes Z (1984). *Az akác (Robinia pseudoacacia L.) (in Hungarian)*. Akadémiai Kiadó, Budapest.

Kiss A, Wilson R, Bariska I (2010). "An experimental 392 year documentary–based multi-proxy (vine and grain) reconstruction of May–July temperatures for Kőszeg, West–Hungary." *International Journal of Biometeorology*, **55**, 595–611.

Kleinbaum D, Klein M (2012). *Survival analysis: a self-learning text (third edition)*. Statistics for biology and health. Springer. ISBN 1441966455.

Kobori H, Dickinson J, Washitani I, Sakurai R, Tatsuya A, Komatsu N, Kitamura W, Takagawa S, Koyama K, Ogawara T, Miller-Rushing AJ (2016). "Citizen science: a new approach to advance ecology, education and conservation." *Ecological Research*, **31**, 1–9.

Koch E, Bruns E, Chmielewski F, Defila C, Lipa W, Menzel A (eds.) (2009a). *Guidelines for plant phenological observations*. World Meteorological Organization.

Koch E, Dittmann E, Lippa W, Menzel A, Nekovár J, Sparks T, van Vliet A (2009b). "COST725 – Establishing a European phenological data platform for climatological applications: major results." *Advances in Science and Research*, **3**, 119–122.

Koch E, Donelly A, Lipa W, Menzel A, Nekovár J (eds.) (2009c). *Final scientific report of COST 725 – Establishing a European dataplatform for climatological applications*. European Cooperation in the field of Scientific and Technical Research, Brussels.

Koch E, Scheifinger H (2004). "Phenology as a biological indicator for a warming Europe." *World Resource Review*, **16**, 173–182.

Körner C, Basler D (2010). "Phenology under global warming." *Science*, **327**, 1461–1462.

Kovats R, Valentini L, Bouwer E, Georgopolou D, Jacob E, Rounsevell M, Soussana J (2014). "Europe." In V Barros, C Field, D Dokken, M Mastrandrea, K Mach, T Bilir, M Chatterjee, K Ebi, Y Estrada, R Genova, B Girma, E Kissel, A Levy, S MacCracken, P Mastrandrea, L White (eds.), *Climate change 2014: Impacts, adaptation and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Krüzselyi I, Bartholy J, Horányi A, Pieczka I, Pongrácz R, Szabó P, Szépszó G, Torma C (2011). "The future climate characteristics of the Carpathian Basin based on a regional climate model mini-ensemble." *Advances in Science and Research*, **6**, 69–73.

Kubin E, Kotilainen E, Poikolainen J, Hokkanen T, Nevalainen S, Pouttu A, Karhu J, Pasanen J (2007). "Monitoring instructions of the Finnish national phenological network." *Technical report*, Finnish Forest Research Institute (Metla), Muhos Research Unit.

Lappalainen H, Linkosalo T, Venalainen A (2008). "Long-term trends in spring phenology in a boreal forest in central Finland." *Boreal Environment Research*, **13**, 303–318.

Lauscher A, Lauscher F (1981). "Vom Einfluss der Temperatur auf die Belaubung der Rosskastanie nach den Beobachtungen in Genf seit 1808." *Wetter und Leben*, **33**, 103–112.

Lavoie C, Lachance D (2006). "A new herbarium-based method for reconstructing the phenology of plant species across large areas." *American Journal of Botany*, **93**, 512–516.

Lee T, Zwiers F, Hegerl G, Zhang X, Tsao M (2005). "A Bayesian climate change detection and attribution assessment." *Journal of Climate*, **18**, 2429–2440.

Lehoczky A, Szabó B, Pongrácz R, Szentkirályi F (2016). "Applicability of flowering onset time series for a proxy of temperature – based on Transylvanian phenological observations from the 19th century." *Applied Ecology and Environmental Research*, **14**, 213–233.

Lieth H (1974). *Phenology and seasonality modeling.* Ecological studies 8, Springer V.

Lima ALA, Rodal MJN (2010). "Phenology and wood density of plants growing in the semi-arid region of north-eastern Brazil." *Journal of Arid Environments*, **11**, 1363–1373.

Lopez-Moreno J, Vicente-Serrano S, Moran-Tejeda E, Lorenzo-Lacruz J, Kenawy A, Beniston M (2011). "Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains: observed relationships and projections for the 21st century." *Global and Planetary Change*, **77**, 62–76.

Mair L, Hill JK, Fox R, Botham M, Brereton T, Thomas C (2014). "Abundance changes and habitat availability drive species' responses to climate change." *Nature Climate Change*, **4**, 127–131.

Mándl E (2009). *Az Észak-Atlanti Oszcilláció hatása a Kárpát–medence térségének éghajlatára (B.Sc. thesis in Hungarian).* Eötvös Loránd University, Budapest.

Mann HB (1945). "Nonparametric tests against trend." *Econometrica*, **13**, 245–259.

Mann M, Bradley R, Hughes M (1999). "Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations." *Geophysical Research Letters*, **26**, 759–762.

Margary I (1926). "The Marsham phenological record in Norfolk, 1736–1925, and some others." *Quarterly Journal of the Royal Meteorological Society*, **52**, 27–54.

Maronna R, Martin R, Yohai V (2006). *Robust Statistics: Theory and Methods.* John Wiley & Sons, New York. ISBN 978-0-470-01092-1.

Martinková J, Smilauer P, Mihulka S (2002). "Phenological pattern of grassland species: relation to the ecological and morphological traits." *Flora*, **197**, 290 – 302.

Masson-Delmotte V, Schulz M, Abe-Ouchi A, Beer J, Ganopolski A, González-Rouco J, Jansen E, Lambeck K, Luterbacher J, Naish T, Osborn T, Otto-Bliesner B, Quinn T, Ramesh R, Rojas M, Shao X, Timmermann A (2013). "Information from paleoclimate archives." In T Stocker, D Qin, GK Plattner, M Tignor, S Allen, J Boschung, A Nauels, Y Xia, V Bex, P Midgley (eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Maurer C, Koch E, Hammerl C, Hammerl T, E P (2009). "BACCHUS temperature reconstruction for the period 16th to 18th centuries from Viennese and Klosterneuburg grape harvest dates." *Journal of Geophysical Research: Atmospheres*, **14**, D22106.

McMaster G, Wilhelm W (1997). "Growing degree-days: one equation, two interpretations." *Agricultural and Forest Meteorology*, **87**, 291–300.

Meier U (2001). "BBCH-Monograph: growth stages of mono- and dicotyledonous plants." *Technical Report 2. Edition*, Federal Biological Research Centre for Agriculture and Forestry.

Meier U, Bleiholder H, Buhr L, Feller C, Hack H, Hess M, Lancashire P, Schnock U, Stauss R, van den Boom T, Weber E, Zwerger P (2009). "The BBCH system to coding the phenological growth stages of plants – history and publications." *Journal of Kulturpflanzen*, **61**, 41–52.

Memmott J, Craze PG, Waser NM, Price MV (2007). "Global warming and the disruption of plant pollinator interactions." *Ecology Letters*, **10**, 710–717.

Menzel A (2000). "Trends in phenological phases in Europe between 1951 and 1996." *International Journal of Biometeorology*, **44**, 76–81.

Menzel A (2002). "Phenology: it's importance to the global change community." *Climatic Change*, **54**, 379–385.

Menzel A (2003). "Plant phenological anomalies in Germany and their relation to air temperature and NAO." *Climatic Change*, **57**, 243–263.

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

Menzel A, Seifert H, Estrella N (2005). "SSW to NNE – North Atlantic Oscillation affects the progress of seasons across Europe." *Global Change Biology*, **11**, 909–918.

Menzel A, Seifert H, Estrella N (2011). "Effects of recent warm and cold spells on European plant phenology." *International Journal of Biometeorology*, **55**, 921–932.

Menzel A, Sparks TH, Estrella N, Koch E, Aasa A, Ahas R, Alm-Kuebler K, BissolliI P, Braslavska O, Briede A, Chmielewski FM, Crepinsek Z, Curnel Y, Dahl A, Defila C, Donelly A, Filella Y, Jatczak K, Mage F, Mestre A, Nordli A, Penuelas J, Pirinen P, Remisova V, Scheifinger H, Striz M, Susnik A, van Vliet AJH, Wielgolaski FE, Zach S, Zust A (2006). "European phenological response to climate change matches the warming pattern." *Global Change Biology*, **12**, 1969–1976.

Migliavacca M, Sonnentag O, Keenan TF, Cescatti A, O'Keefe J, Richardson AD (2012). "On the uncertainty of phenological responses to climate change, and implications for a terrestrial biosphere model." *Biogeosciences*, **9**, 2063–2083.

Mikkonen S, Laine M, Mäkelä H, Gregow H, Tuomenvirta H, Lahtinen M, Laaksonen A (2015). "Trends in the average temperature in Finland, 1847–2013." *Stochastic Environmental Research and Risk Assessment*, **29**, 1521–1529.

Miller-Rushing A, Hoye T, Inouye D, Post E (2010). “The effects of phenological mismatches on demography.” *Philosophical Transactions of the Royal Society, B: Biological Sciences*, **365**, 3177–3186.

Miller-Rushing A, Inouye DW, Primack R (2008). “How well do first flowering dates measure plant responses to climate change? The effects of population size and sampling frequency.” *Journal of Ecology*, **96**, 1289–1296.

Miller-Rushing A, Primack R (2008). “Global warming and flowering times in Thoreau’s Concord: a community perspective.” *Ecology*, **89**, 332–341.

Miller-Rushing A, Primack R, Bonney R (2012). “The history of public participation in ecological research.” *Frontiers in Ecology and the Environment*, **10**, 285–290.

Moller A, Rubolini D, Lehikoinen E (2008). “Populations of migratory bird species that did not show a phenological response to climate change are declining.” *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 16195–16200.

Molnár A, Tökölyi J, Végvári Z, Sramkó G, Sulyok J, Barta Z (2012). “Pollination mode predicts phenological response to climate change in terrestrial orchids: a case study from central Europe.” *Journal of Ecology*, **100**, 1141–1152.

Montoya J, Raffaelli D (2010). “Climate change, biotic interactions and ecosystem services.” *Philosophical Transactions of the Royal Society, B: Biological Sciences*, **365**, 2013–2018.

Morisette J, Richardson A, Knapp A, Fisher J, Graham E, Abatzoglou J, Wilson B, Breshears D, Henebry G, Hanes J, Liang L (2009). “Tracking the rhythm of the seasons in the face of global change: phenological research in the 21st century.” *Frontiers in Ecology and the Environment*, **7**, 253–260.

Nekovár J, Koch E, Kubin E, Nejedlik P, Sparks T, Wielgolaski F (2008). “COST Action 725 – The history and current status of plant phenology in Europe.” *Technical report*, COST Office, Brussels.

Newman JA, Anand M, Henry HAL, Hunt S, Gedalof Z (2011). *Climate change biology*. CAB International, Wallingford (UK) and Cambridge (USA). ISBN 978-1-84593-748-5.

Niedžwiedž T, Jatczak K (2008). “History of phenology in Poland.” In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe*. COST Office, Brussels.

Nord EA, Lynch JP (2009). "Plant phenology: a critical controller of soil resource acquisition." *Journal of Experimental Botany*, **60**, 1927–1937.

Ovaskainen O, Skorokhodova S, Yakovleva M, Sukhov A, Kutenkov A, Kutenkovab N, Shcherbakovb A, Meykea E, del Mar Delgado M (2013). "Community-level phenological response to climate change." *Proceedings of the National Academy of Sciences of the United States of America*, **110**, 13434–13439.

Parmesan C (2006). "Ecological and evolutionary responses to recent climate change." *Annual Review of Ecology, Evolution, and Systematics*, **37**, 637–669.

Parmesan C, Burrows M, Duarte C, Poloczanska E, Richardson A, Schoeman D, Singer M (2013). "Beyond climate change attribution in conservation and ecological research." *Ecology letters*, **16**, 58–71.

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

Parry M, Canziani O, Palutikof J, van der Linden P, Hanson C (2007). "Technical summary." In *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Pau S, Wolkovich E, Cook B, Davies T, Kraft N, Bolmgren K, Betancourt J, Cleland E (2011). "Predicting phenology by integrating ecology, evolution and climate science." *Global Change Biology*, **17**, 3633–3643.

Pauling A, Luterbacher J, Casty C, Wanner H (2006). "Five hundred years of gridded high-resolution precipitation reconstruction over Europe and the connection to large-scale circulation." *Climate Dynamics*, **26**, 387–405.

Penuelas J, Filella I, Zhang X, Llorens L, Ogaya R, Lloret F, Comas P, Estiarte M, Terradas J (2004). "Complex spatio-temporal phenological shifts as a response to rainfall changes." *New Phytologist*, **161**, 837–846.

Penuelas J, Rutishauser T, Filella I (2009). "Phenology feedbacks on climate change." *Science*, **324**, 887–888.

Penuelas J, Sardans J, Estiarte M, Ogaya R, Carnicer J, Coll M, Barbeta A, Rivas-Ubach A, Llusia J, Garbulsky M, Filella I, Jump A (2013). "Evidence of current impact of climate change on life: a walk from genes to the biosphere." *Global Change Biology*, **19**, 2303–2338.

Pettorelli N (2012). "Climate change as a main driver of ecological research." *Journal of Applied Ecology*, **49**, 542–545.

Pettorelli N, Vika J, Mysterud A, Gaillard JM, Tucker C, Stenseth N (2005). “Using the satellite-derived NDVI to assess ecological responses to environmental change.” *Trends in Ecology and Evolution*, **20**, 503–510.

Pieczka I, Bartholy J, Pongrácz R, Hunyady A (2010). “Climate change scenarios for Hungary based on numerical simulations with a dynamical climate model.” In I Lirkov, S Margenov, J Wazniewski (eds.), *Large-scale scientific computing.* Springer Berlin Heidelberg.

Pilar C, Gabriel M (1998). “Phenological pattern of fifteen Mediterranean phanaerophytes from *Quercus ilex* communities of NE-Spain.” *Plant Ecology*, **139**, 103–112.

Poloczanska E, Brown C, Sydeman W, Kiessling W, Schoeman D, Moore P, Brander K, Bruno J, Buckley L, Burrows M, Duarte C, Halpern B, Holding J, Kappel C, O’Connor M, Pandolfi J, Parmesan C, Schwing F, Thompson S, Richardson A (2013). “Global imprint of climate change on marine life.” *Nature Climate Change*, **3**, 919–925.

Pongrácz R, Bartholy J, Miklós E (2011). “Analysis of projected climate change for Hungary using ENSEMBLES simulations.” *Applied Ecology and Environmental Research*, **9**, 387–398.

Popovič T, Drljevic M (2008). “History and current status of phenology in Montenegro.” In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe.* COST Office, Brussels.

Porter J, Parry M, Carter T (1991). “The potential effects of climatic change on agricultural insect pests.” *Agricultural and Forest Meteorology*, **57**, 221–240.

Post E (2013). *Ecology of climate change: the importance of biotic interactions.* Princeton University Press. ISBN 978-0-691-14847-2.

Primack R, Higuchi H, Miller-Rushing A (2000). “The impact of climate change on cherry trees and other species in Japan.” *Biological Conservation*, **142**, 1943–1949.

Pudas E, Leppala M, Tolvanen A, Poikolainen J, Venalainen A, Kubin E (2008). “Trends in phenology of *Betula pubescens* across the boreal zone in Finland.” *International Journal of Biometeorology*, **52**, 251–259.

Puppi G (2007). “Origin and development of phenology as a science.” *Italian Journal of Agrometeorology*, **3**, 24–29.

R Development Core Team (2015). *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL `http://www.R-project.org`.

Rafferty N, CaraDonna P, Bronstein J (2015). "Phenological shifts and the fate of mutualisms." *Oikos*, **124**, 14–21.

Ramakrishna RN, Keeling CD, Hashimoto H, Jolly W, Piper SC, Tucker C, Myneni R, Running S (2003). "Climate–driven increases in global terrestrial Net Primary Production from 1982 to 1999." *Science*, **300**, 1560–1563.

Rawal D, Kasel S, Keatley M, Nitschke C (2015). "Herbarium records identify sensitivity of flowering phenology of eucalypts to climate: implications for species response to climate change." *Austral Ecology*, **40**, 117–125.

Remisová T, Nejedlik P (2008). "History and present observations in Slovak plant phenology." In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe*. COST Office, Brussels.

Réthly A (1936). "Hazánk részvétele a növényfejlődés (fenológia) nemzetközi megfigyelésében (in Hungarian)." *Erdészeti Közlemények*, **75**, 1029–1036.

Richardson AD, Keenan TF, Migliavacca M, Ryu Y, Sonnentag O, Toomey M (2013). "Climate change, phenology, and phenological control of vegetation feedbacks to the climate system." *Agricultural and Forest Meteorology*, **169**, 156–173.

Robbirt K, Davy A, Hutchings M, Roberts D (2011). "Validation of biological collections as a source of phenological data for use in climate change studies: a case study with the orchid *Ophrys sphegodes*." *Journal of Ecology*, **99**, 235–241.

Roberts A (2010). "Smoothing methods." In I Hudson, M Keatley (eds.), *Phenological research – methods for environmental and climate analysis*. Springer, London.

Robinet C, Roques A (2010). "Direct impacts of recent climate warming on insect populations." *Integrative Zoology*, **5**, 132–142.

Rodriguez G (2007). "Lecture notes on Generalized Linear Models – Chapter 7: survival models." *Technical report*, Princeton University.

Rodriguez-Galiano V, Dash J, Atkinson P (2015). "Characterising the land surface phenology of Europe using decadal MERIS data." *Remote Sensing*, **7**, 9390–9409.

Roekaerts M (2002). “The biogeographical regions map of Europe: basic principles of its creation and overview of its development.” *Technical report*, European Topic Centre Nature Protection and Biodiversity, European Environment Agency.

Romanovskaja D, Baksiene E (2008). “Phenological investigations in Lithuania.” In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe*. COST Office, Brussels.

Root T, MacMynowski D, Mastrandrea M, Schneider S (2005). “Human–modified temperatures induce species changes: joint attribution.” *Proceedings of the National Academy of Sciences*, **21**, 7465–7469.

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

Rosemartin A, Crimmins T, F ECA, Gerst KL, Kellermann JL, Posthumus EE, Denny EG, Guertin P, Marsh L, Weltzin JF (2014). “Organizing phenological data resources to inform natural resource conservation.” *Biological Conservation*, **173**, 90–97.

Rosenzweig C, Karoly D, Vicarelli M, Neofotis P, Wu Q, Casassa G, Menzel A, Root TL, Estrella N, Seguin Bea (2008). “Attributing physical and biological impacts to anthropogenic climate change.” *Nature*, **453**, 353–357.

Rousseeuw P, Croux C, Todorov V, Ruckstuhl A, Salibian-Barrera M, Verbeke T, Koller M, Maechler M (2015). *Robustbase: basic robust statistics*. R Foundation for Statistical Computing; package version 0.92-3.

Ruml M, Milatovic D, Vulic T, Vukovic A (2011). “Predicting apricot phenology using meteorological data.” *International Journal of Biometeorology*, **55**, 723–732.

Rutishauser T, Luterbacher J, Jeanneret F, Pfister C, Wanner H (2007). “A phenology based reconstruction of interannual changes in past spring seasons.” *Journal of Geophysical Research*, **112**, G04016.

Rutishauser T, Schleip C, Sparks TH, Nordli O, Menzel A, Wanner H, Jeanneret F, Luterbacher J (2009). “Temperature sensitivity of Swiss and British plant phenology from 1753 to 1958.” *Climate Research*, **39**, 179–190.

Sala O, Chapin F, Armesto J, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke L, Jackson R, Kinzig1 A, Leemans R, Lodge D, Mooney H, Oesterheld M, Poff N, Sykes M, Walker B, Walker M, Wall D (2000). "Global biodiversity scenarios for the year 2100." *Science*, **237**, 1770–1774.

Schaber J (2012). *Pheno: auxiliary functions for phenological data analysis.* R Foundation for Statistical Computing; package version 1.6.

Schaber J, Badeck FW (2002). "Evaluation of methods for the combination of phenological time series and outlier detection." *Tree Physiology*, **22**, 973–982.

Scheifinger H, Menzel A, Koch E, Peter C, Ahas R (2002). "Atmospheric mechanisms governing the spatial and temporal variability of phenological phases in Central Europe." *International Journal of Climatology*, **22**, 1739–1755.

Scheifinger H, Meran I, Szabó B, Gallaun H Natali S, Mantovani S (2016). "Temperature sensitivity of a numerical pollen forecast model." In *Research Abstracts of the ESA 2016: 6th European Symposium on Aerobiology of the European Aerobiological Society (Lyon, France)*, p. 307.

Scheifinger H, Templ B (2016). "Is citizen science the recipe for the survival of paper-based phenological networks in Europe?" *Bioscience*, **66**, 533–534.

Schieber B, Janík R, Snopková Z (2009). "Phenology of four broad-leaved forest trees in a submountain beech forest." *Journal of Forest Science*, **55**, 15–22.

Schleip C, Menzel A, Estrella N, Dose V (2006). "The use of Bayesian analysis to detect recent changes in phenological events throughout the year." *Agricultural and Forest Meteorology*, **141**, 179–191.

Schleip C, Sparks TH, Estrella N, Menzel A (2009). "Spatial variation in onset dates and trends in phenology across Europe." *Climate Research*, **39**, 249–260.

Schwartz M (2013). *Phenology: an integrative environmental science.* Springer Science & Business Media. ISBN 940-0-769-253.

Schwartz M, Reiter B (2000). "Changes in North American spring." *International Journal of Climatology*, **20**, 929–932.

Schwartz MD (1999). "Advancing to full bloom: planning phenological research for the 21st century." *International Journal of Biometeorology*, **42**, 113–118.

Schwartz MD (2008). "History of lilac phenological observations in the USA." *Technical report*, Iowa State University, Western Research and Demonstration Farm, Report: ISRF08-10.

Schwartz MD, Ahas R, Aasa A (2006). “Onset of spring starting earlier across the Northern Hemisphere.” *Global Change Biology*, **12**, 343–351.

Settele J, Scholes R, Betts R, Bunn S, Leadley P, Nepstad D, Overpeck J, Taboada M (2014). “Terrestrial and inland water systems.” In C Field, V Barros, D Dokken, K Mach, M Mastrandrea, T Bilir, M Chatterjee, K Ebi, Y Estrada, R Genova, B Girma, E Kissel, A Levy, S MacCracken, P Mastrandrea, L White (eds.), *Climate change 2014: impacts, adaptation and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Silverton J (2009). “A new dawn for citizen science.” *Trends in Ecology and Evolution*, **24**, 467–471.

Sneyers R (1990). *On the statistical analysis of series of observations.* World Meteorological Organization, Geneva.

Solga M, Harmon J, Ganguli A (2014). “Timing is everything: an overview of phenological changes to plants and their pollinators.” *Natural Areas Journal*, **34**, 227–234.

Sonnentag O, Hufkens K, Teshera-Sterne C, Young A, Friedl M, Braswell B, Milliman T, O‘Keefe J, Richardson A (2012). “Digital repeat photography for phenological research in forest ecosystems.” *Agricultural and Forest Meteorology*, **152**, 1–19.

Sparks T, Carey P (1995). “The responses of species to climate over two centuries: an analysis of the Marsham phenological record, 1736–1947.” *Journal of Ecology*, **83**, 321–329.

Sparks T, Menzel A (2002). “Observed changes in season: an overview.” *International Journal of Climatology*, **22**, 1715–1725.

Sparks TH, Górska-Zajaczkowska M, Wójtowicz W, Tryjanowski P (2011). “Phenological changes and reduced seasonal synchrony in western Poland.” *International Journal of Biometeorology*, **55**, 447–453.

Sparks TH, Huber K, Croxton P (2006). “Plant development scores from fixed-date photographs: the influence of weather variables and recorder experience.” *International Journal of Biometeorology*, **50**, 275–279.

Sparks TH, Jeffree EP, Jeffree CE (2000). “An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK." *International Journal of Biometeorology*, **44**, 82–87.

StatSoft I (2003). *Statistica 6.1 – STATISTICA*. Data Analysis Software.

Stenseth NC, Mysterud A, Ottersen G, Hurrell J, Chan KS, Lima M (2002). "Ecological effects of climate fluctuations." *Science*, **297**, 1292–1296.

Stenseth NC, Ottersen G, Hurrell J, Mysterud A, Lima M, Chan K, Yoccoz N, Adlandsvik B (2003). "Studying climate effects on ecology through the use of climate indices: the North Atlantic Oscillation, El Nino Southern Oscillation and beyond." *Proceedings of the Royal Society of London. Series B: Biological Sciences*, **270**, 2087–2096.

Stocker T, Qin D, Plattner GK, Tignor M, Allen S, Boschung J, Nauels A, Xia Y, Bex V, Midgley P (2013). "Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth assessment report of the Intergovernmental Panel on Climate Change." Cambridge, United Kingdom and New York, NY, USA.

Stoeckli R, Vidale P (2004). "European plant phenology and climate as seen in a 20-year AVHRR land-surface parameter dataset." *International Journal of Remote Sensing*, **25**, 3303–3330.

Stoller L (1956). "A note on Thoreau's place in the history of phenology." *The University of Chicago Press Journals*, **47**, 172–181.

Strand J (2000). "Some agrometeorological aspects of pest and disease management for the 21st century." *Agricultural and Forest Meteorology*, **103**, 73–82.

Szabó B, Lehoczky A, Filzmoser P, Templ M, Szentkirályi F, Pongrácz R, Ortner T, Mert C, Czúcz B, Team S (2014). "From South to North: flowering phenological responses at different geographical latitudes in 12 European countries." In *Geophysical Research Abstracts of the European Geosciences Union (EGU) 2014*, pp. EGU2014–9489.

Szabó B, Vincze E, Czúcz B (2016). "Flowering phenological changes in relation to climate change in Hungary." *International Journal of Biometeorology*, **60**, 1347–1356.

Szalai S, Bella S, Németh A, Dunay S (2008). "History of Hungarian phenological observations." In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe*. COST Office, Brussels.

Templ B, Fleck S, Templ M (2016). “Change of plant phenophases explained by survival modelling.” *International Journal of Biometeorology.* doi:10.1007/s00484-016-1267-z.

Templ B, Templ M, Filzmoser P, Lehoczky A, Baksiene E, Fleck S, Gregow H, Hodzic S, Kálvane G, Kubin E, Palm V, Romanovskaja D, Vučetić V, Žust A, Czúcz B, NS-Pheno-Team (2017). “Phenological patterns of flowering across biogeographical regions of Europe.” *International Journal of Biometeorology.* doi:10.1007/s00484-017-1312-6.

Thackeray S, Henrys P, Hemming D, Bell J, Botham M, Burthe S, Helaouet P, Johns D, Jones I, Leech D, Mackay E, Massimino D, Atkinson S, Bacon P, Brereton TM, Carvalho L, Clutton-Brock T, Duck C, Edwards M, Elliott J, Hall S, Harrington R, Pearce-Higgins J, Høye T, Kruuk L, Pemberton J, Sparks T, Thompson P, White I, Winfield I, Wanless S (2016). “Phenological sensitivity to climate across taxa and trophic levels.” *Nature*, **535**, 241–245.

Thackeray S, Sparks T, Frederiksen M, Burthe S, Bacon P, Bell J, Botham M, Brereton T, Bright P, Carvalho L, Clutton-Brock T, Dawson A, Edwards M, Elliott J, Harrington R, Johns D, Jones I, Jones J, Leech D, Roy D, Scott W, Smith M, Smithers R, Winfield I, Wanless S (2010). “Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments.” *Global Change Biology*, **16**, 3304–3313.

Therneau T (2015). *R package survival – a package for survival analysis in S.* R Foundation for Statistical Computing; package version 2.38-3.

Thomas C, Ohlemüller R, Anderson B, Hickler T, Miller P, Sykes M, Williams J (2008). “Exporting the ecological effects of climate change.” *EMBO Reports*, **9**, 28–33.

Thomson L, Macfadyen S, Hoffmann A (2010). “Predicting the effects of climate change on natural enemies of agricultural pests.” *Biological Control*, **52**, 296–306.

Thuiller W, Lavorel S, Araújo M, Sykes MT, Prentice I (2005). “Climate change threats to plant diversity in Europe.” *Proceedings of the National Academy of Sciences*, **102**, 8245–8250.

Thuller W (2007). “Biodiversity: climate change and the ecologist.” *Nature*, **448**, 550–552.

Todorov V, Filzmoser P (2009). *Multivariate robust statistics: methods and computation.* Südwestdeutscher Verlag für Hochschulschriften, Saarbruecken, Germany.

Tookey F, Battey N (2010). “Temperate flowering phenology.” *Journal of Experimental Botany*, **61**, 2853–2862.

Trigo RM, Osborn T, Corte-Real JM (2002). “The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms.” *Climate Research*, **20**, 9–17.

Tulloch AIT, Possingham HP, Joseph LN, Szabo J, Martin TG (2013). “Realising the full potential of citizen science monitoring programs.” *Biological Conservation*, **165**, 128–138.

van der Loo MPJ (2010). *Distribution based outlier detection in univariate data.* Statistics Netherlands, The Hague/Heerlen.

Vanasch M, Salis L, Holleman L, van Lith B, Visser M (2013). “Evolutionary response of the egg hatching date of a herbivorous insect under climate change.” *Nature Climate Change*, **3**, 244–248.

Varga Z, Varga-Haszonits Z, Enzsölné Gerencsér E, Lantos Z, Milics G (2009a). “A fekete bodza (*Sambucus nigra* L.) fejlődésének bioklimatológiai elemzése (in Hungarian).” *Kertgazdaság*, **41**, 66–79.

Varga Z, Varga-Haszonits Z, Enzsölné Gerencsér E, Lantos Z, Milics G (2009b). “A kislevelű hárs (*Tilia cordata* L.) fejlődésének bioklimatológiai elemzése (in Hungarian).” *Acta Agronomica Ovariensis*, **51**, 21–38.

Varga Z, Varga-Haszonits Z, Enzsölné Gerencsér E, Lantos Z, Milics G (2010). “A májusi orgona (*Syringa vulgaris* L.) fejlődésének bioklimatológiai elemzése (in Hungarian).” *Klíma-21 Füzetek – Klímaváltozás–hatások–válaszok*, **60**, 22–35.

Varga Z, Varga-Haszonits Z, Enzsölné Gerencsér E, Lantos Z, Milics G (2012). “Bioclimatological analysis of black locust (*Robinia pseudoacacia* L.) development (in Hungarian).” *Acta Agronomica Ovariensis*, **54**, 35–52.

Visser ME, Both C (2005). “Shifts in phenology due to global climate change: the need for a yardstick.” *Proceedings of the Royal Society Biology*, **272**, 2561–2569.

Visser ME, Caro S, van Oers K, Schaper S, Helm B (2010). “Phenology, seasonal timing and circannual rhythms: towards a unified framework.” *Philosophical Transactions of the Royal Society, B: Biological Sciences*, **365**, 3113–3127.

Visser ME, Holleman LJM, Gienapp P (2006). “Shifts in caterpillar biomass phenology due to climate change and its impact on the breeding biology of an insectivorous bird.” *Oecologia*, **147**, 164–172.

Vučetić V, Vučetić M, Lončar Z (2008). "History and present observations in Croatian plant phenology." In J Nekovár, E Koch, E Kubin, P Nejedlik, T Sparks, FE Wielgolaski (eds.), *COST Action 725 – The history and current status of plant phenology in Europe*. COST Office, Brussels.

Walkovszky A (1998). "Changes in phenology of the locust tree (*Robinia pseudoacacia* L.) in Hungary." *International Journal of Biometeorology*, **41**, 155–160.

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

Wang H, Ge Q, Dai J, Z T (2015). "Geographical pattern in first bloom variability and its relation to temperature sensitivity in the USA and China." *International Journal of Biometeorology*, **59**, 961–969.

Wang H, Rutishauser T, Dai J (2016). "Impacts of global warming on phenology of spring leaf unfolding remain stable in the long run." *International Journal of Biometeorology*. doi:10.1007/s00484-016-1210-3.

Wang K, Dickinson E, Wild M, Liang S (2010). "Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002: 2. Results." *Journal of Geophysical Research: Atmospheres*, **115**, D20113.

Way D (2011). "Tree phenology responses to warming: spring forward, fall back?" *Tree Physiology*, **31**, 469–471.

White MA, Hoffman F, Hargrove WW, Nemani RR (2005). "A global framework for monitoring phenological responses to climate change." *Geophysical Research Letters*, **32**, L04705.

Wickham H (2007). "Reshaping data with the reshape package." *Journal of Statistical Software*, **21**, 1–20.

Wickham H (2009). *ggplot2: elegant graphics for data analysis*. Springer-Verlag New York. ISBN 978-0-387-98140-6.

Wielgolaski F (2001). "Phenological modifications in plants by various edaphic factors." *International Journal of Biometeorology*, **45**, 196–202.

Wilczek A, Burghardt L, Cobb A, Cooper M, Welch S, Schmitt J (2010). "Genetic and physiological bases for phenological responses to current and predicted climates." *Philosophical Transactions of the Royal Society, B: Biological Sciences*, **365**, 3129–3147.

Williams JW, Jackson ST, Kutzbach JE (2007). “Projected distributions of novel and disappearing climates by 2100 AD.” *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 5738–5742.

Williams T, Bourgeon S, Cornell A, Ferguson L, Fowler M, Fronstin R, Love O (2015). “Mid-winter temperatures, not spring temperatures, predict breeding phenology in the European starling *Sturnus vulgaris*.” *Royal Society Open Science*, **2**, 140301.

Wolkovich E, Cook B, Allen J, Crimmins T, Betancourt J, Travers S, Pau S, Regetz J, Davies T, Kraft N, Ault T, Bolmgren K, Mazer S, McCabe G, McGill B, Parmesan C, Salamin N, Schwartz M, Cleland E (2012). “Warming experiments underpredict plant phenological responses to climate change.” *Nature*, **485**, 494–497.

Wolkovich E, Davies T, Schaefer H, Cleland E, Cook B, Travers S, Willis C, Davis C (2013). “Temperature-dependent shifts in phenology contribute to the success of exotic species with climate change.” *American Journal of Botany*, **100**, 1407–1421.

Yang L, Rudolf V (2010). “Phenology, ontogeny and the effects of climate change on the timing of species interactions.” *Ecology Letters*, **13**, 1–10.

Zarnetske P, Skelly D, Urban M (2012). “Biotic multipliers of climate change.” *Science*, **336**, 1516–1518.

Zeng H, Jia G, Epstein H (2011). “Recent changes in phenology over the northern high latitudes detected from multi-satellite data.” *Environmental Research Letters*, **6**, 045508.

Zhang X, Friedl M, Schaaf C, Strahler A, Hodges J, Gaoa F, Reedb B, Huete A (2003). “Monitoring vegetation phenology using MODIS.” *Remote Sensing of Environment*, **84**, 471–475.

Zsilinszki A (2014). *A 2012–13-as tél szinoptikus sajátosságainak értékelése NAO, AO távkapcsolat elemzések bevonásával (PhD dissertation in Hungarian)*. Eötvös Loránd University.

Acknowledgements

First of all I want to thank my supervisor, Dr. Bálint Czúcz, who took over the supervision of my PhD years. Although I have spent several months abroad, I could always find the way back to the Centre for Ecological Research, Hungarian Academy of Sciences, Hungary.

The whole process of my PhD would not have been possible without my husband, PD Dr.techn. Matthias Templ. I cannot even begin to express how much his enduring love, support and belief have carried me through this PhD process. Thanks also for being a fantastic colleague, a patient co-author. I am looking forward to that Templ and Templ publication.

I wish to thank to Prof. Peter Filzmoser, for giving me (as a biologist) the great opportunity to spend months with various grants at the Institute of Statistics and Mathematical Methods in Economics, Vienna University of Technology (Austria) and learn statistics, furthermore to develop my programming skills in R.

I am beyond thankful to Dr. Sándor Szalai (Szent István University, Hungary), who made possible for me to participate at the first international conference of my life (Phenology 2010: Conference on Climate change impacts and adaptations in Dublin, Ireland) and through I have known the core people of the international phenologist community at early stage of my career. Dr. Ferenc Szentkirályi also deserves my special thanks for opening my eyes on the topic of phenology during my research years as a Bachelor student at the Plant Protection Institute, Hungarian Academy of Sciences.

Besides, I am grateful to other people who shared the experience of writing papers with me, especially Annamária Lehoczky (Centre for Climate Change, University Rovira i Virgili, Spain), Stefan Fleck (Statistics Austria, Austria) and the NS-Pheno Team (a group of researchers who provided data that were used to build up a North–South transect based phenological database). In person I thank

to Eugenija Bakšiene and Danuta Romanovskaja (Institute of Agriculture, Voke Branch of the Lithuanian Research Centre for Agriculture and Forestry; Lithuania), Hilppa Gregow (Climate Service Centre, Finnish Meteorological Institute; Finnland), Sabina Hodzic (Sector for Applied Meteorology, Federal Hydrometeorological Institute of Federation of Bosnia and Herzegovine; Bosnia and Herzegovine), Katarzyna Jatczak (Institute of Meteorology and Water Management, Centre for Poland's Climate Monitoring; Poland), Gunta Kalvane (Faculty of Geography and Earth Sciences, University of Latvia; Latvia), Eero Kubin (Natural Resources and Bioproduction, Natural Resources Institute Finland; Finnland), Tadeusz Niedžwiedž (Faculty of Earth Sciences, University of Silesia; Poland), Vello Palm (Institute of Ecology and Eart Science, University of Tartu; Estonia), Tonka Popovič (Department for Agrometeorology, Hydrometeorological Institute of Montenegro; Montenegro, Zora Snopkova and Pavol Nejedlik (Slovak Hydrometeorological Institute; Slovakia), Silvana Stevkova (Department of Climatology and Agrometeorology, Hydrometeorological Service of the Republic of Macedonia; Macedonia), Višnja Vučetić (Meteorological and Hydrological Service; Croatia) and Ana Žust (Environmental Agency of the Republic of Slovenia, Meteorological Office; Slovenia).

This PhD would not have been the same without my skills I have gained from work experience abroad during my internship positions in the United Kingdom (Department of Life Sciences, Imperial College London, London), in Austria (Institute of Statistics and Probability Theory, Vienna University of Technology and Secretariat of the Carpathian Convention, United Nations Environmental Program (UNEP), Vienna) and in Switzerland (Agricultural Meteorology Division, World Meteorological Organization (WMO), Geneva). Therefore, I thank for the opportunity to Dr. Blake Suttle, Dr. Harald Egerer and Dr. Jose Camacho.

I wish to thank Dr. Elisabeth Koch and Dr. Christoph Matulla from the

Zentralanstalt für Meteorologie und Geodynamik (ZAMG, Austria) for giving me the opportunity for collaboration. I would especially like to show my gratitude for his support to Dr. Helfried Scheifinger (Department of Climatology, ZAMG), who shared his knowledge in the area of climatology and pollen-biology.

I would like to thank both preliminary reviewers, Dr. János Podani and Dr. Tibor Kalapos (Department of Plant Systematics, Ecology and Theoretical Biology, Eötvös Loránd University) for their insightful suggestions on the dissertation and Karin Zorn (University of Vienna, Austria) for proofreading some sections; their comments led to an improvement of the work.

Last but not least, I want to thank my family and friends for their devoted support and patience.

Publication list

Refereed research papers

1. **Szabó, B.**, Vincze, E. and Czúcz, B. (2016): Flowering phenological changes in relation to climate change in Hungary. *International Journal of Biometeorology*, 60: 1347–1356; doi: 10.1007/s00484-015-1128-1. Impact factor: 2.309.[†]

2. **Templ, B.**, Templ, M., Filzmoser, P., Lehoczky, A., Bakšiene, E., Fleck, S., Gregow, H., Hodzic, S., Kalvane, G., Kubin, E., Palm, V., Romanovskaja, D., Vučetič, V., Žust, A., Czúcz, B. and NS-Pheno-Team (2017): Phenological patterns of flowering across biogeographical regions of Europe – accepted (19.01.2017) in *International Journal of Biometeorology*, doi: 10.1007/s00484-016-1267-z. Impact factor: 2.309.

3. **Templ, B.**, Fleck, S. and Templ, M. (2016): Change of plant phenophases explained by survival modelling. *International Journal of Biometeorology*, doi: 10.1007/s00484-016-1267-z. Impact factor: 2.309.

4. Lehoczky, A., **Szabó, B.**, Pongrácz, R. and Szentkirályi, F. (2016): Applicability of flowering onset time series for a proxy of temperature – based on Transylvanian phenological observations from the 19th century. *Applied Ecology and Environmental Research*, 14: 213–233; doi: 10.15666/aeer/1402–213233. Impact factor: 0.557.

5. Scheifinger, H. and **Templ, B.** (2016): Is citizen science the recipe for the survival of paper-based phenological networks in Europe? *BioScience*, 66: 533–534; doi:10.1093/biosci/biw069. Impact factor: 4.294.

6. **Szabó, B.**, Nagy, B. and Szentkirályi, F. (2014): Long-term (1958–2009) changes in hatching time of grasshopper (*Orthoptera*) species – consequences of climate change in Hungary. (in Hungarian: Egyenesszárnyú (*Orthoptera*) fajok lárvakelés kezdetének hosszú-távú változásai (1958-2008) az éghajlatváltozás következményeként Magyarországon.) *Állattani Közlemények*, 99: 45–59.[‡]

[†] The thesis author was nominated and became the winner of the European Meteorological Society (EMS) Tromp Award 2016 for this paper. The Tromp Foundation is funding this award with the intention to promote biometeorology in Europe, as a recognition for outstanding achievements in biometeorology.

[‡] This publication is not included in the present thesis.

CURRICULUM VITAE

Personal Data

Name	Barbara Templ (maiden name: Barbara Szabó)
Born	October 9, 1987 in Budapest, Hungary
Nationality	Hungarian
Marital status	Married

Education and Qualifications

2011 – 2013	Master of Science in Biology at Eötvös Loránd University in Budapest, Hungary
2006 – 2011	Bachelor of Science in Biology at Eötvös Loránd University in Budapest, Hungary

Current Positions

March. 2017 –	**Intern** at Agricultural Meteorology Division, World Meteorological Organization, Switzerland
May. 2016 –	**PhD Candidate** at Eötvös Loránd University, Hungary

Fellowships and Awards

2016	**EMS Tromp Award** awarded by the European Meteorological Society and the Tromp Foundation
2015	**FEMtech Praktika für Studentinnen** at Zentralanstalt für Meteorologie und Geodynamik, Austria
2015	**ERASMUS Scholarship** at Vienna University of Technology, Austria
2014	**Ernst Mach Scholarship** at Vienna University of Technology, Austria
2013	**Campus Hungary Scholarship** at Vienna University of Technology, Austria
2012	**Fellowship granted by the Republic of Hungary** awarded by the Minister of Education, Hungary
2012	**ERASMUS Scholarship** at Imperial College London, United Kingdom
2012	**Youth Talent of the Inner City** awarded by the Mayor of 5th district of Budapest, Hungary
2012	**Outstanding Student of the Faculty** awarded by the Faculty of Science, ELTE, Hungary

Professional Experience

15 May. 2017* –	**Junior Researcher.** Department of Climatology, Zentralanstalt für Meteorologie und Geodynamik (ZAMG), Vienna, Austria.
1 Mar. 2017 –	**Internship in Programme Management.** Agricultural Meteorology Division, World Meteorological Organization (WMO), Geneva, Switzerland.
1 Mar. 2016 – 31 Dec. 2016	**Junior Researcher in Modelling and Pollen forecast.** Department of Climatology, Zentralanstalt für Meteorologie und Geodynamik (ZAMG), Vienna, Austria.
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15 Jun. 2015 – 30 Sep. 2015	**Internship in Programme Management.** Secretariat of the Carpathian Convention, United Nations Environmental Program (UNEP), Vienna, Austria.
1 Feb. 2015 – 31 May. 2015	**Research Internship in Classification and Discriminant Analysis.** Institute of Statistics and Mathematical Methods in Economy, Vienna University of Technology (TU Wien), Austria.
1 Sep. 2014 – 31 Dec. 2014	**Research Internship in Multivariate Statistics and Data Analysis.** Institute of Statistics and Probability Theory, TU Wien, Austria.
30 Sep. 2013 – 30 Nov. 2013	**Research Internship in Multivariate Statistic and Data Analysis.** Institute of Statistics and Probability Theory, TU Wien, Austria.
18 Jun. 2012 – 18 Sep. 2012	**Research Internship in Community Ecology and Global Change.** Section of Ecology and Evolution, Dept. of Life Sciences, Imperial College London, UK.
1 Sep. 2012 – 1 Sep. 2013	**Junior Researcher** at the Hungarian Meteorological Service, Budapest, Hungary.
1 Feb. 2011 – 1 Jun. 2013	**Master Research Student** at Plant Protection Institute, Hungarian Academy of Sciences (HAS) and Dept. of Systematic Zoology and Ecology, Eötvös Loránd University.
1 Sep. 2008 – 31 May 2009	**Bachelor Research Student** at Plant Protection Institute (HAS) and Dept. of Plant Systematics, Ecology and Theoretical Biology, Eötvös Loránd University.

ADATLAP

a doktori értekezés nyilvánosságra hozatalához*

I. A doktori értekezés adatai

A szerző neve: Templ Barbara Andrea

MTMT-azonosító: 10050702

A doktori értekezés címe és alcíme: Applications and new developments in phenological research: monitoring, modelling and outlook

DOI-azonosító: 10.15476/ELTE.2017.016

A doktori iskola neve: Biológia Doktori Iskola

A doktori iskolán belüli doktori program neve: Ökológia, konzervációbiológia és szisztematika

A témavezető neve és tudományos fokozata: Dr. Czúcz Bálint, PhD

A témavezető munkahelye: European Topic Center on Biological Diversity (Párizs, Franciaország) valamint MTA Ökológiai Kutatóközpont, Ökológiai és Botanikai Intézet (Vácrátót, Magyarország)

II. Nyilatkozatok

1. A doktori értekezés szerzőjeként

a) hozzájárulok, hogy a doktori fokozat megszerzését követően a doktori értekezésem és a tézisek nyilvánosságra kerüljenek az ELTE Digitális Intézményi Tudástárban. Felhatalmazom a Természettudományi kar Dékáni Hivatal Doktori, Habilitációs és Nemzetközi Ügyek Csoportjának ügyintézőjét, hogy az értekezést és a téziseket feltöltse az ELTE Digitális Intézményi Tudástárba, és ennek során kitöltse a feltöltéshez szükséges nyilatkozatokat.

b) kérem, hogy a mellékelt kérelemben részletezett szabadalmi, illetőleg oltalmi bejelentés közzétételéig a doktori értekezést ne bocsássák nyilvánosságra az Egyetemi Könyvtárban és az ELTE Digitális Intézményi Tudástárban;

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d) kérem, hogy a mű kiadására vonatkozó mellékelt kiadó szerződésre tekintettel a doktori értekezést a könyv megjelenéséig ne bocsássák nyilvánosságra az Egyetemi Könyvtárban, és az ELTE Digitális Intézményi Tudástárban csak a könyv bibliográfiai adatait tegyék közzé. Ha a könyv a fokozatszerzést követőn egy évig nem jelenik meg, hozzájárulok, hogy a doktori értekezésem és a tézisek nyilvánosságra kerüljenek az Egyetemi Könyvtárban és az ELTE Digitális Intézményi Tudástárban.

2. A doktori értekezés szerzőjeként kijelentem, hogy

a) az ELTE Digitális Intézményi Tudástárba feltöltendő doktori értekezés és a tézisek saját eredeti, önálló szellemi munkám és legjobb tudomásom szerint nem sértem vele senki szerzői jogait;

b) a doktori értekezés és a tézisek nyomtatott változatai és az elektronikus adathordozón benyújtott tartalmak (szöveg és ábrák) mindenben megegyeznek.

3. A doktori értekezés szerzőjeként hozzájárulok a doktori értekezés és a tézisek szövegének plágiumkereső adatbázisba helyezéséhez és plágiumellenőrző vizsgálatok lefuttatásához.

Kelt: Budapest, 2017. 02. 10.

Barbara Templ

a doktori értekezés szerzőjének aláírása