DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS
23

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CHANGES IN PHENOLOGICAL TIME SERIES IN ESTONIA AND CENTRAL AND EASTERN EUROPE 1951–1998.

RELATIONSHIPS WITH AIR TEMPERATURE AND ATMOSPHERIC CIRCULATION

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I Ahas, R., Jaagus, J., Aasa, A. 2000. The phenological calendar of Estonia and its correlation with mean air temperature. International Journal of Biometeorology, 44(4), pp. 159–166.

II Ahas, R., Aasa, A. 2005. The effects of climate change on the phenology of selected Estonian plant, bird and fish populations. International Journal of Biometeorology. *Submitted.*

III Ahas, R., Aasa, A., Menzel, A., Fedotova, V.G., Scheifinger, H. 2002. Changes in European spring phenology. International Journal of Climatology, 22, pp. 1727–1738.

IV Aasa, A., Jaagus, J., Ahas, R., Sepp, M. 2004. The influence of atmospheric circulation on plant phenological phases in Central and Eastern Europe. International Journal of Climatology, 24 (12): 1551–1564.

V Ahas, R., Aasa, A., 2003. Developing Comparative Phenological Calendars. In Schwartz, M.D. (Ed.), Phenology: An Integrative Environmental Science, 39, Kluwer Academic Publishers, Dordrecht. pp 301–318.

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V Database 60%, Methodology 50%; Data analysis 70%; Writing 30%; Cartography 80%.

1. INTRODUCTION

Phenology is the study of the seasonal events of organisms influenced by periodic environmental changes such as temperature changes driven by weather and climate. A phenological phase (phenophase) is the stage of growth of an organism, for example the beginning of flowering, buds opening, ripening of fruits, autumn colouring and so on. Phenological phases are important indicators for detecting the impacts of a changing climate on organisms and ecosystems, as they reflect the complicated combination of environmental changes in visually measurable form. Because of this, phenological time series have been recorded during the last centuries, and can today be used as valuable sources for studying the impacts of climate change. Phenological applications are also important in agriculture and horticulture. The accurate prediction of pollination can substantially help allergists.

The data of phenological observations have been systematically recorded in many countries and international networks. In Europe, phenology has been the focus of various scientists since the studies of Carl Linne. Over time, phenologists have observed various plant-, bird-, insect-, fish- and animal species (Lieth, 1974; Schnelle, 1955; Schults, 1981).

The main objectives of this dissertation are: 1) to summarise phenological trends in Estonia and Central and Eastern Europe, 2) to analyse their relationship with changes in climate. On the basis of our phenological studies, I argue that spring and summer phenology (AMJJA) has advanced significantly in Estonia and Central and Eastern Europe during last 50 years (Aasa, 2001; Ahas, 1999; Ahas, 2001; Ahas et al., 2000). These phenological trends have the highest rate of change in the Baltic Sea region, which also covers Estonia, with slope values of up to –0.3 to –0.4 days per year (Ahas et al., 2002; Chmielewski and Rötzer, 2001; Fabian and Menzel, 1999; Menzel, 2000; Menzel and Estrella, 2001; Menzel and Fabian, 1999).

As the timing of spring and summer phenology in the Temperate Zone is mostly driven by temperature regime, I assume that the phenological changes detected in Estonia and Europe were caused by changes in the temperature regime (Ahas and Aasa 2005; Ahas et al., 2000). Temperature regime has changed in Estonia for the winter and spring period (FMAM) significantly because of the changed atmospheric circulation in the winter months (JFM) (Jaagus et al., 2003; Keevallik et al., 1999). Spring and summer phenology; spring temperature and atmospheric circulation in winter have a significant correlation with each other in Estonia and in Europe (Aasa et al., 2004; Menzel and Sparks, 2005). There is an interesting temporal lag between the changed factors: circulation indices have significant changes during winter (JFM); this influences temperature in the following winter and spring months (JFMAM) which influences phenological phases during later spring and summer months

(AMJJA). I assume that circulation change during winter and early spring influences the phenology during the following spring and summer because of the temperature accumulation by plants and temperature inertia in the environment. The presence of temperature inertia may be one reason why phenological trends have higher rates of change near the Baltic Sea as this region is under the direct influence of westerly air masses and the sea has a good accumulation capacity. Other explanations to these phenomena may be that changes in winter (NAO and/or temperature) can directly influence winter dormancy conditions, which determines the phenology for the whole of the following growing season.

2. DATA

Estonian phenological data

Estonia is located on the eastern coast of the Baltic Sea, between 57.5°N and 59.5°N. The western part of Estonia lies under the direct influence of the sea, while in the central and eastern parts of the country, the climate gradually becomes more continental.

We used phytophenological data from the EMHI (Estonian Meteorological and Hydrological Institute) observation program covering the time period from 1951–1999 at 15 observation stations (Figure 1). In total, 938 time-series (one phase of one species observed in one station) of trees and bushes (409), fruit trees and berry bushes (185), field crops (220), potatoes (75) and grasses (49) were used. Species and phases are not evenly distributed between the 15 stations. The monthly distribution of studied phases is presented in Figure 2. The growing season starts in April, and that month has more than 100 phases, May has more than 300 phases, June more than 150 phases and July more than 100 phases.

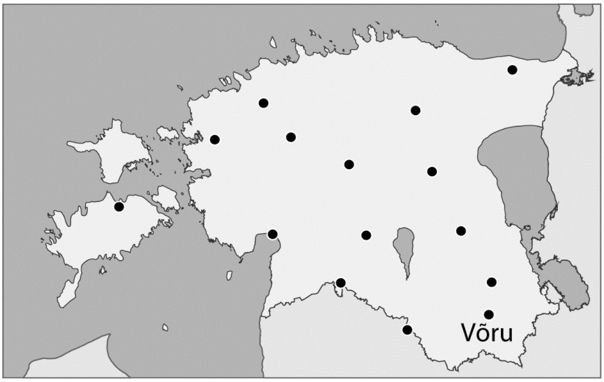

Figure 1. Map of Estonian phenological data series used in analyses.

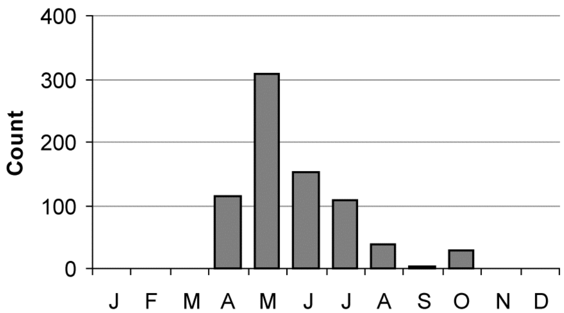

Figure 2. Monthly distribution of phytophenological phases in the studied Estonian dataset.

All of the phenological observation data used were recorded using agri-meteorological observation station methods, which are similar to the methods employed in the former USSR (Davitaja, 1964). The beginning of a phenological phase was recorded when an activity was observed in 10% of the individuals of a population. The example of the Võru phenological calendar, with 14 phases, is given in Table 1.

Table 1. Example of the one page of the Võru phenological calendar and slopes of linear trends (* – P<0.05).

Species	Phase	Average	St.-Dev.	Slope
Betula pendula Roth.	Sap bleeding	8–Apr	9.0	–0,19*
Corylus avellana L.	Flowering	13–Apr	12.0	–0.15
Betula pendula Roth.	Foliation	6–May	6.6	–0.15*
Prunus padus L.	Foliation	6–May	7.5	–0.18*
Acer platanoides L.	Flowering	8–May	7.3	–0.2*
Tilia cordata Mill.	Foliation	16–May	8.0	–0.18*
Prunus padus L.	Flowering	17–May	7.2	–0.18*
Malus domestica Borkh.	Flowering	24–May	7.2	–0.16*
Syringa vulgaris L.	Flowering	26–May	8.0	–0.16*
Sorbus aucuparia L.	Flowering	30–May	7.9	–0.14
Secale cereale L.	Ear formation	5–Jun	8.0	0.00
Tilia cordata Mill.	Flowering	12–Jul	7.2	–0.05
Ribes nigrum L.	Ripeness	19–Jul	8.0	–0.04
Malus domestica Borkh.	Defoliation	16–Oct	7.5	–0.05

European phenological data

The phytophenological data set originates from the European plant phenological database, which has been compiled under the European Union 5th Framework Programme project, entitled *POSITIVE* (Phenological Observations and Satellite Data (NDVI): Trends in the Vegetation Cycle in Europe) in 2001 (Menzel, 2002; Menzel et al., 2001a). The period under observation is 1951–1998. For our current analysis, the best time series of six common phases at 104 observation stations within the period 1951–1998 was chosen (Figure 3.). The databases used in this study provide relatively good coverage of Germany, Poland, the Baltic States, Russia, Byelorussia and Ukraine. The Scandinavian countries stopped carrying out phenological observation programs in the 1950s and 1960s, and therefore do not have pertinent data from recent times. The only data publicly available from the Scandinavian countries is from the International

Phenological Gardens (IPG) network, which operates some stations in Scandinavia.

All observations are presumed to have been made at the same location. The minimum number of observation years required for statistical analyses was 35.

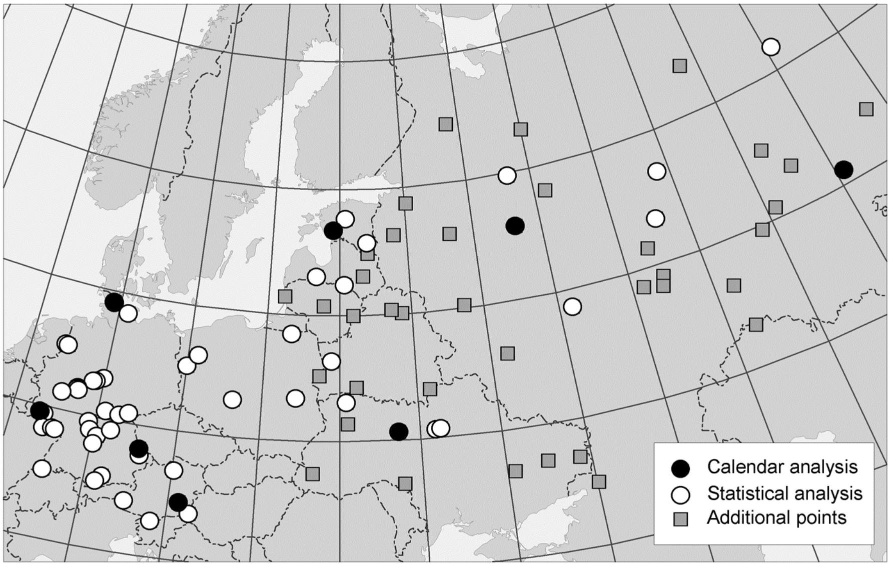

Figure 3. Map of observation sites used in analysis (Ahas et al., 2002).

Climate data

Estonian diurnal air temperature data comes from 19 EMHI weather stations during the period 1951–1999. Monthly mean air temperatures used for the study were observed at the same stations as those at which phenological observations were performed.

Data concerning soil temperature originates from the Võru station for the period 1954–1999. The soil temperature is recorded daily at depths of 0.2, 0.8, 1.6 and 3.2 meters.

Atmospheric circulation data

Atmospheric circulation is characterized both by circulation indices and by the monthly frequency of circulation types, distinguished by two classifications. Both the North Atlantic oscillation (NAO) index and the Arctic oscillation (AO) index characterize the westerly airflow or the intensity of the zonal circulation

(Hurrell and van Loon, 1997; Thompson and Wallace, 1998). The NAO index is defined as the difference in normalized sea-level pressure between the Azores high and the Icelandic low. Positive values denote a large air pressure gradient and a strong westerly airflow, and negative values indicate a small pressure gradient in the North Atlantic, which leads to a weakening of the westerlies. The AO index describes atmospheric circulation over a much larger area, indicating the intensity of the circumpolar vortex (Thompson and Wallace, 1998). The NAO can be viewed as an expression of the AO in the North Atlantic.

The atmospheric circulation classification that was constructed at the Arctic and Antarctic Research Institute in St. Petersburg by Vangengeim and Girs was initially designed for making long-term weather forecasts for the Arctic Ocean shipping lane (Vangengeim, 1952). According to this, atmospheric circulation patterns are classified into three basic circulation forms, W, E and C, mainly according to the thermobaric wave position in the upper troposphere (Figure 4).

The Hess and Brezowsky classification system, also known as the Grosswetterlagen, reflects atmospheric circulation in central Europe. The classification is based on circulation types, which are distinguished on the basis of (1) the position of large pressure centres (Azores high/Icelandic low), (2) the position of frontal zones, and (3) the cyclonicity or anticyclonicity of the circulation (Bardossy and Caspary, 1990; Gerstengarbe and Werner, 1999). In this classification, individual circulation types are divided into three groups: zonal (Z), half-meridional (H), and meridional (M) (Figure 5).

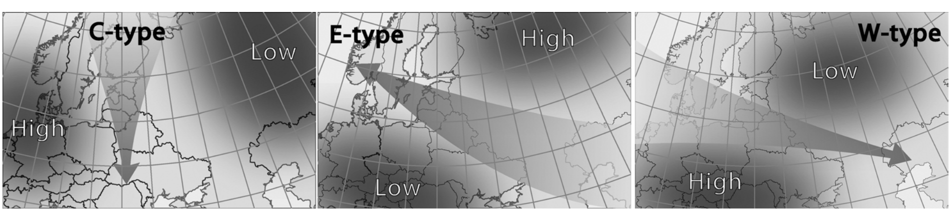

Figure 4. Simplified diagrams of Vangengeim-Girs circulation types. ‚High' and 'Low' mark the location of the main air pressure centres (Aasa et al., 2004).

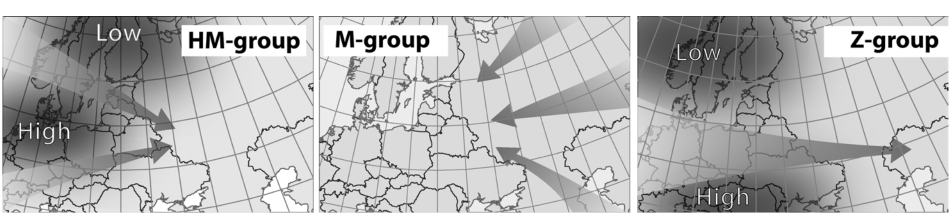

Figure 5. Simplified diagrams of Hess-Brezowsky circulation groups. ‚High' and ‚Low' mark the main air pressure centres (Aasa et al., 2004).

3. METHODS

Geographical overview

The study has two geographical focuses: Estonia and Central and Eastern Europe. I first present the results of Estonian studies, as we have a very good database, and experience concerning local conditions. Estonia is located on the eastern coast of the Baltic Sea, between 57.5°N and 59.5°N. The western part of Estonia lies under the direct influence of the sea, while in the central and eastern parts of the country, the climate gradually becomes more continental. For some examples of correlations with soil temperature, we used material from Võru station in south-eastern Estonia, because this station has 50 years of phenological and soil observations at the same station.

In the second part of our study, I present a broader area that we here refer to as Central and Eastern Europe. We define the area from Germany in the west (45°N, 7°E) to the eastern border of Europe (65°N, 63°E), Ural Mountains in Russia) and from Estonia in the north (58°N, 24°E) to Ukraine in the south (47°N, 37°E) as central Europe, because the eastern part of study area has a relatively small number of phases. This area was selected because of the focus of the 5th EU Framework project, *POSITIVE* (Menzel, 2002). This study was part of the *POSITIVE* project. A broader perspective helps to understand local processes in Estonia and to investigate broader environmental processes such as the impact of atmospheric circulation.

Interpolation gaps in the observation data

The phenological database used in this study consists of about 20% interpolated gaps. In order to fill in the gaps in the phenological time-series, we have used the interpolation method, based on the best correlations (Ahas and Aasa, 2003a), using the following steps. From the correlation matrixes of all time series, we selected those with the highest correlations. The selection was finalized among those with high correlations, by selecting the best time-series, using the criteria of a temporally close phase at the same station or the same phase at the geographically closest station. Then the mean interval between the observed dates of two time-series was calculated. Finally, the gaps were replaced with dates calculated on the basis of the mean interval and real observation in the selected time-series.

Describing changes in phenological calendars

Trends at the beginning of phenophases are analyzed using linear regression analysis and presented in the form of changes in days per year. The basic period was 50 years from 1951 to 2000, with small deviations, as we used different data sources in different studies. For example, if the slope of a 50-year time-series trend is –0.30 days/year, then it has become 15 days earlier during the entire period under observation. Trends are considered significant on the level of $P < 0.05$.

Correlations with atmospheric circulation

Linear correlation analysis was used to assess the strength and direction of the relationships between the beginning of phenological phases and atmospheric circulation. The correlation coefficients were calculated separately for each phase. The objective of correlation analyses was to study the influence of atmospheric circulation on the timing of phenological phases.

The results were mapped using spatial interpolation on the basis of the Kriging method (Legendre and Legendre, 1998). The statistical significance of the correlation coefficients was checked at random and, as a result, relationships stronger than ±0.3 proved to be statistically significant.

For the Vangengeim–Girs and Hess–Brezowsky classifications, the parameters of the following months/seasons were used: January, February, March, April, May; spring (March–May), winter (December–February), and the cold half of the year (November–March). The NAO indices for January, February, March, April, May, December–February, January–March, February–April and March–May were considered. Of the AO indices, in addition to those of the first 3 months of the year, the values for December–February, March–May and November–March were also used. The circulation parameters of June and later months were excluded from further analysis, since all three phases begin before June.

4. PHENOLOGICAL CHANGES

Estonia

The trends phytophenological time series gathered from 1951–1999 in Estonia have been summarized in several studies (Ahas, 1999; Ahas et al., 2002; Ahas et al., 2005). The distribution of statistically significant trends in all Estonian datasets shows that both spring and summer phases have become earlier during the last 49 years: 138 of the studied time series have advanced significantly (by 10 to 15 days) over 49 years (slope: –0.2 to –0.3); 112 time series by 5 to 10 (slope: –0.1 to –0.2) and 53 time-series by 15 to 20 days over the 49-year study period (Figure 6). There were 32 time series that advanced by more than 20 days over the 49 years, all of which were statistically significant ($P<0.05$). 151 of the time series have advanced by 0 to 5 days, but the trends are not significant. 93 of the phytophenological time series have been delayed, 20 of which have a statistically significant trend with a delay between 5 and 30 days over the study period. The delayed time series that display significant trends are mainly autumn phases such as the ripening of fruits and seeds (*Ribes nigrum, Ribes rubrum, Secale cereale*), the colouring and falling of leaves (*Ribes nigrum, Ribes rubrum, Malus domestica*) and in summer, the end of flowering (*Malus domestica*).

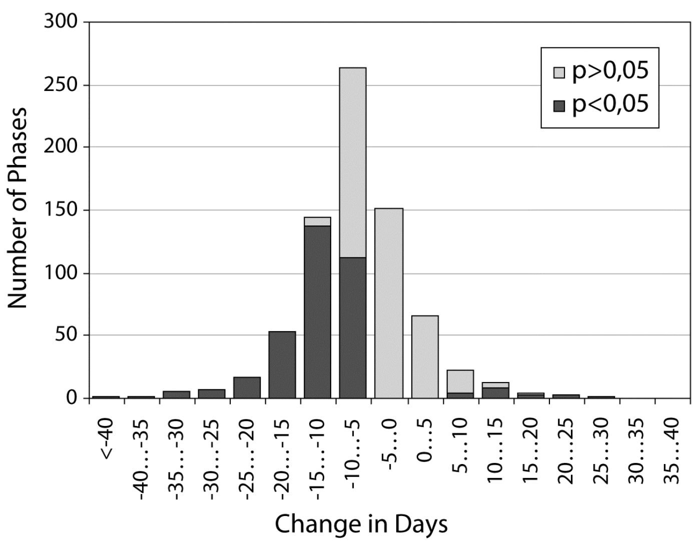

Figure 6. The distribution of trends in the Estonian phytophenological time series (1951–1999) according to the size and significance of changes (Ahas et al., 2005).

Delays in the onset of phases have, for example, occurred in the expanding of the shoots of some fruit trees and bushes (*Ribes uva-crispa, Ribes rubrum, Malus domestica*), and also in the beginning of crops and the ending of flowering. Several authors have noted that the delay in the expanding of shoots can be related to the increased risk of spring frost events during warmer and earlier springs (Kramer et al., 1996; Linkosalo et al., 2000; Scheifinger et al., 2003).

Figure 7 describes the annual distribution of phenological changes. The polynomial trend (3rd) shows the mean change at the beginning of phases during the growing period. The distribution of changes is similar to that studied earlier: changes are greater in spring and less in summer (Ahas et al., 2002). In autumn there is a trend towards positive changes, which means that phenophases are delayed in autumn. Historical changes in phenological time-series in Estonia have also been studied. During the period 1919–1996 the change in spring phenophases was –3 to –14 days over 81 years (Ahas, 1999; Ahas et al., 1998).

The spatial distribution of phenological trends shows that the western Estonian maritime climate has advanced more than in the continental inland areas or in northern Estonia. For example, the ear of rye (*Secale cereale*, variety "Sangaste") has advanced by 10 to 12 days (slope: 0.2–0.24) in western Estonia, and by 2 to 4 days (slope: 0.04–0.08) in eastern Estonia (Ahas et al., 2005).

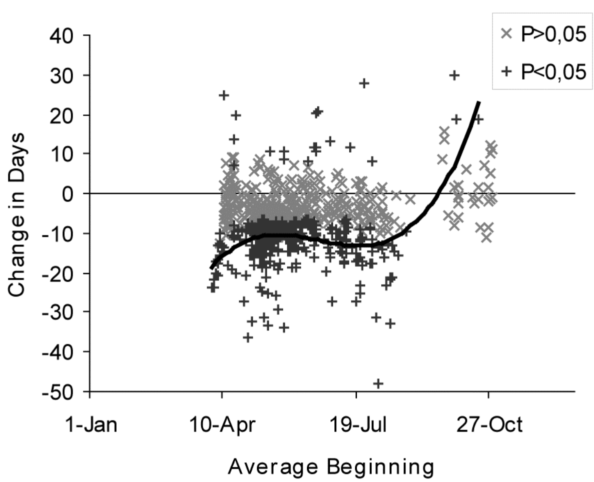

Figure 7. Annual distribution of slopes of phenological trends of phases in Estonia. The polynomial (3rd) trend is added to describe the distribution of significant trends.

In the Estonian phenological dataset, the distribution of phenologically early and late springs was also analyzed. These were determined using a threshold of values greater or less than 1 standard deviation in all spring phases, i.e. measurements outside of the ±1 standard deviation threshold were considered to be either early or late accordingly. Results show that at the beginning of the period (in the 1950s), there were more delayed phases, reaching a peak in 1955 with a total of 87 delayed phases (Figure 8). The number of delayed time series decreased between 1955 and 1995. Years that are earlier by more than 1 standard deviation begin to dominate after 1987, reaching a peak in 1989, with 77 advanced phases. In 1990, 1991, 1992 and 1993, the majority of the time series were also advanced (Ahas et al., 2005).

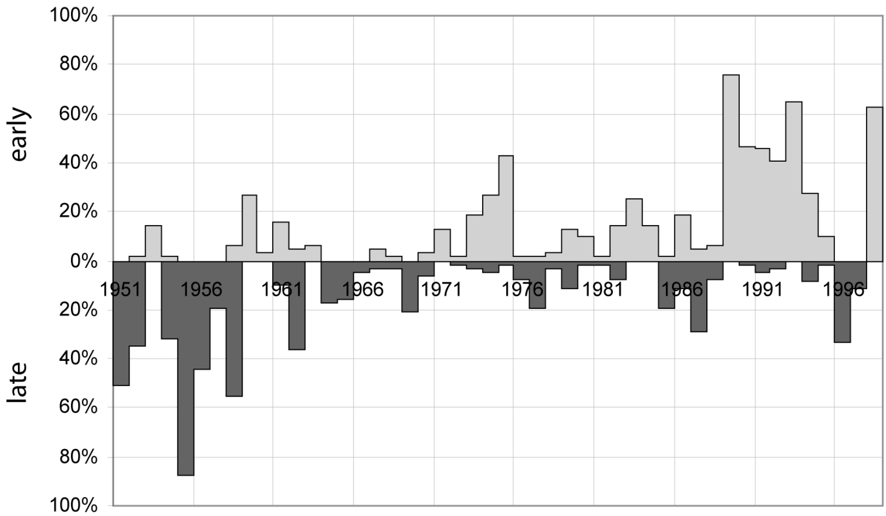

Figure 8. The percentage of values larger or smaller than ± 1 standard deviation in the summarised phenological calendar of 3 selected stations in Estonia (Pärnu, Türi and Võru) (Ahas and Aasa, 2003a).

Central and Eastern Europe

Phenological trends in Central and Eastern Europe studied by the 5th EU Framework Programme, Project *POSITIVE* (Menzel, 2002). This project mapped phenological trends on the Southern and Eastern coasts of the Baltic Sea using data sets of weather services (DWD, EMHI) and the Russian Geographical Society covering the period 1951–1998 (Ahas et al., 2002; Scheifinger et al., 2003).

Over the last 50 years, phenological time series show the highest rate of change in early spring phases (hazel, colts-foot), which have become 10–20 days earlier over that period (slope: –0.2 to –0.4). This rate of change is similar for all stations except Eastern Europe, where most Eastern stations showed a delay in spring phenology and climatic seasons. In Figure 9, different rhythms and trends in phenological time series are shown for selected stations. Spring phases (birch, lilac, and apple) display smaller changes, with values 5–15 days earlier over the study period. Kuznetskoye has positive slope values (ignoring a very small insignificant negative change for birch) for all studied phases. The flowering of linden, which occurs earlier in summer, displays more significant trends in the Baltic region.

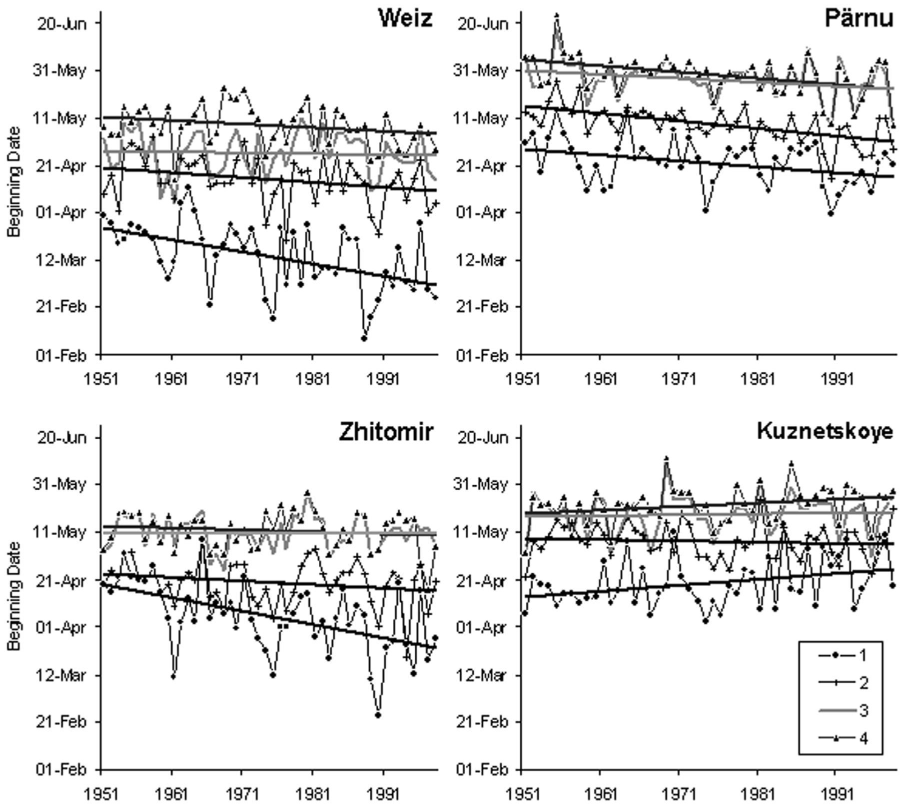

Figure 9. Data series and linear trends of phases at four selected stations: 1, flowering of colts-foot; 2, birch leaf unfolding; 3, flowering of apple; 4, flowering of lilac (Ahas et al., 2002).

To generalise trends over the entire studied area and calendar, the annual distribution of phenological changes is described in Figure 10. The polynomial trend (3rd) describes the average distribution of significant changes during the growing season. In spring and summer, the mean magnitude of changes is approximately 15 days over 48 years, (slope: –0.3). Changes are greater in earlier spring. In autumn the magnitude of the changes is near zero.

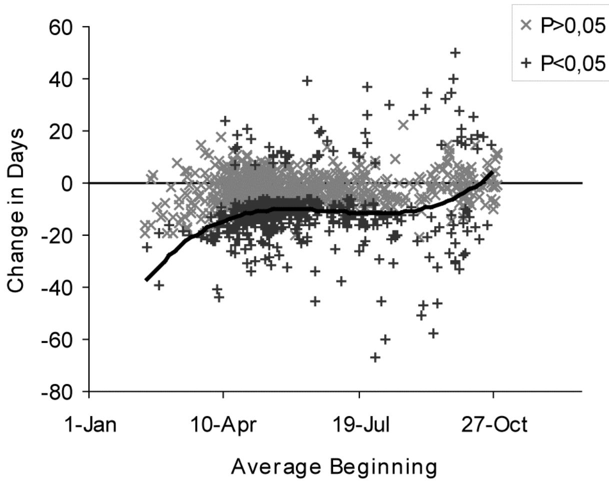

Figure 10. Annual distribution of slopes of 1419 studied phenological trends in Central and Eastern Europe. The polynomial (3rd) trend is added to describe the distribution of significant trends.

A total of 1419 phases were analysed in Central and Eastern Europe. A delay ($P<0.05$) was detected at the beginning of 57 phenophases (4%). It was determined that the fact that changes are greater in the autumn period is a notable tendency. The autumn phases mainly became later in the western part of the studied area (ripening, leaf colouring and defoliation), although no significant changes were detected in the eastern part of the studied area. Statistically significant delays during the spring period occurred mainly in the eastern part of the studied area. The delay in the onset of phases in the western part is related to the registering of the final dates of phenophases (e.g. the end of flowering).

Spatial analysis shows greater changes in spring phenology across the Baltic Sea and Eastern European Plain regions. The map of the linear regression of birch leaf unfolding (Figure 11) show the highest statistically significant slopes, with values of up to –0.3 to –0.6 days per year in the Baltic region. The change of phase is not significant and has a smaller value in Eastern and Central Europe (0.1 to –0.2). For colts-foot, lilac, apple and linden, the Eastern European region has a positive trend value (0.04–0.2) in the mountainous Ural region, at both the Ivdel (60.69 °N, 60.42 °E) and Kuznetskoye (55.5 °N, 60.5° E) stations. The regression map of lilac (Figure 12) shows a similar maximum number of changes in the Baltic region (–0.3 to 0.2); the northern part of the Eastern European Plain also has a higher slope value (–0.2 to 0.1). Some German and Polish stations have a positive slope (0.1–0.3) for the flowering of lilac and linden, which is untypical for this period of the year, and can be explained by the different length of the observation periods and the quality of the data (Figure 13). The studied trends of *Tilia platyphyllos*, which has a better observation series, show different results (Menzel et al., 2001b; Menzel and Fabian, 1999).

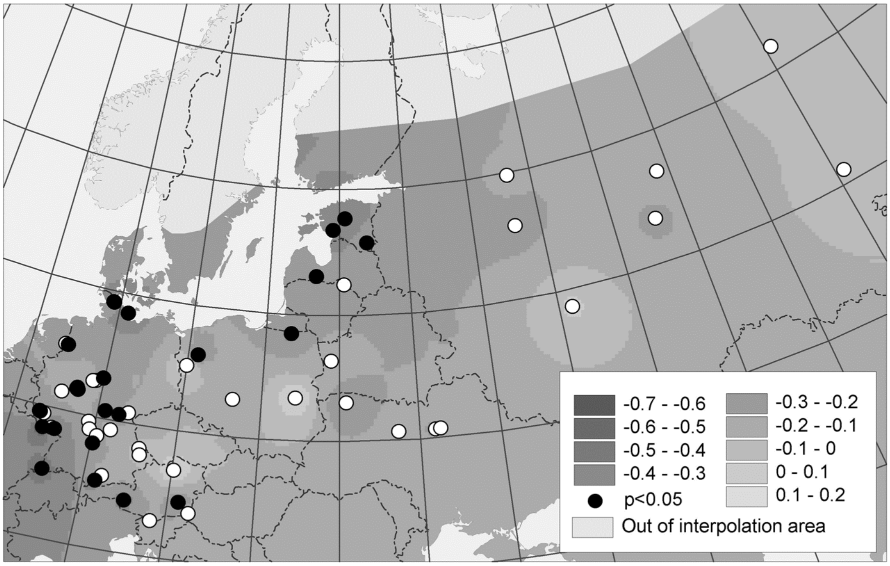

Figure 11. Map of linear trend slopes for birch leaf unfolding, 1951–1998 (Ahas et al., 2002).

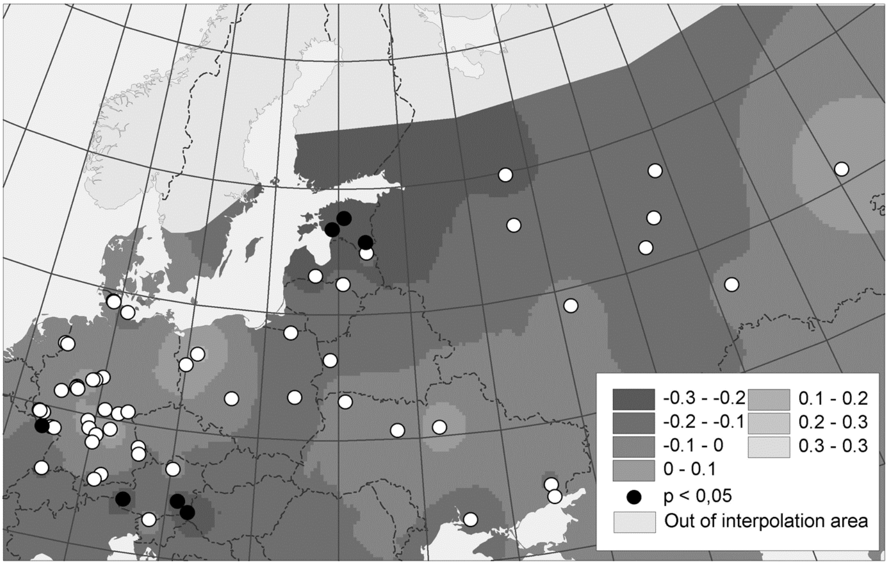

Figure 12. Map of linear trend slopes for flowering of lilac, 1951–1998 (Ahas et al., 2002).

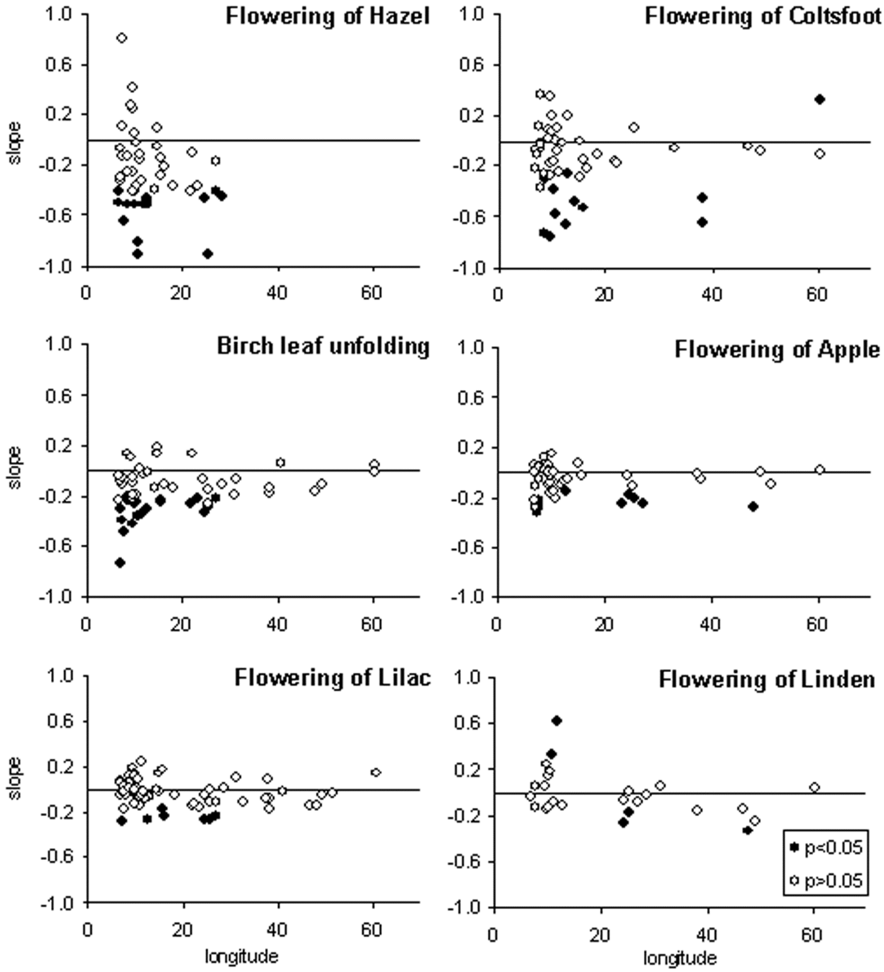

Figure 13. Longitudinal distribution (x-axis) of slope values for the phenological time series studied (Ahas et al., 2002).

5. PHENOLOGY AND CHANGES IN TEMPERATURE REGIME

Phenology and temperature

In order to study phenological trends and use them as indicators of changing climate, it is necessary to study the environmental drivers that cause those changes. This is also an important direction of study to address the right impacts that cause environmental change and to contribute to climate change and policy debate.

Temperature is the main triggering factor for spring and summer phenological events in temperate zones. There are two major temperature parameters that have a high correlation with both spring and summer phases and therefore have been used in most phenological analyses and models. First, the positive temperatures (mean, cumulative etc) during the growing season have a direct triggering influence on plant phenology (Chuine et al., 2003; Schwartz, 2003b; Sparks et al., 2000). The second parameter is the chilling factor, i.e. the negative temperatures during the previous winter, as spring phenology is very dependent on the temperature regime during winter dormancy. The physiological and biochemical mechanisms during dormancy and the end of dormancy have so far not been thoroughly studied (Chuine et al., 2003). The phenological development of plants is also influenced by other environmental factors (radiation, moisture, soil, landscape, ecosystems etc.) and human impacts such as pollution, land use and urban heat islands (Schnelle, 1955; Schwartz, 2003b; White et al., 2002). In the Baltic Sea region, snow cover is an important factor for spring phenology, as it affects temperature inertia and isolates plants from weather impacts.

We have studied temperature correlations with plant phenology for Estonian stations. The highest temperature correlations are demonstrated by phenological phases during April and June, when the correlation coefficient with air temperature of the previous month is –0.6 to –0.8. In Estonia, phases with such high correlations are the flowering of common trees such as rowan, lilac, oak, linden; leaf opening of birch and apple and many similar phases.

The mean monthly temperature and cumulative sums of temperature have a smaller influence on phenophases in the earlier period, i.e. in April or the beginning of May, when phases are more dependent on high temperatures over a few days: pollination of Hazel, the start of the vegetation of rye, flowering of maple. These correlations also have the highest spatial differences in Estonia, as local weather can be very variable in earlier spring. For example, the correlation of the flowering of maple with mean temperature in April was much lower ($R = -0.59$) at the coastal station in Pärnu than at the inland station in Võru ($R = -0.85$).

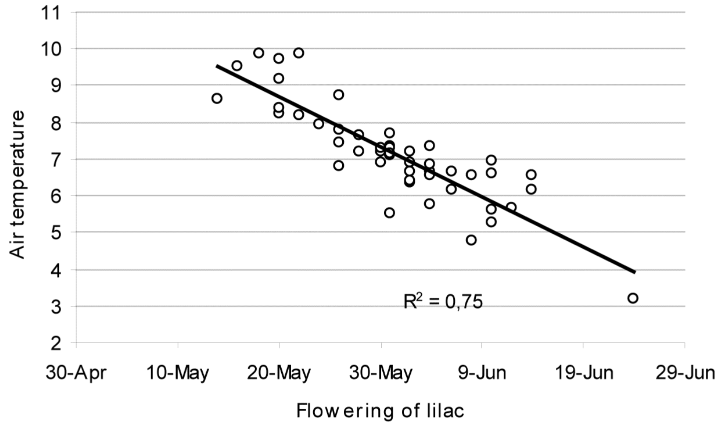

Figure 14. Correlation of flowering of lilac in Türi station with mean air temperature of April and May.

The beginnings of phenological phases in Estonia have the highest correlation with the air temperature of the previous 1–3 months (Figure 14). Owing to the relatively high correlation (r>0.6), mean air temperatures can be used as an alternative to the degree-days method of analyzing the impact of climatic change on phenological phases or the phenological calendar.

Another important aspect of environmental change is soil temperature. Soil temperature is an important environmental parameter, as many plants species actually have higher correlations with soil temperature than air temperature. The impact of soil temperature on plant phenology has been studied by several authors (Hickin and Vittum, 1976; McMaster and Wilhelm, 1998; McMaster and Wilhelm, 2003; Repo et al., 2004; Sorensen and Campbell, 1978). We studied the correlations between plant phenology and soil temperature at Võru station in Estonia. Table 2 shows the differences between correlations with air and soil temperature.

The thermal regime of the soil can be characterised by inertia in the transport of warmth to deeper layers. This means that variations in air temperature are reflected in the soil with some delay. This delay increases with depth. A similar effect can be detected in correlations between the beginning of phenological phases and soil temperature profile. Correlations between monthly soil temperature and the beginning of the flowering of rowan were studied (Figure 15). A strong correlation was detected – the warmer the soil, the earlier the rowan begins to flower. The correlation coefficient is –0.8 in May (at a depth of 0.2 m). The coefficient decreases with depth, and at the depth of 3.2 m the strongest correlation is –0.58, which is reached in July, which is delayed by the response to temperature changes at the end of April and the beginning of May.

Table 2. Strongest correlations (R) between phenophases beginnings and air/soil temperature in months (M) with best correlations.

Species	Phase	Mean Onset	Air		Soil –20		Soil –80		Soil –320	
			R	M	R	M	R	M	R	M
Betula pendula	Sap bleeding	8–Apr	–0.53	Feb	–0.64	May	–0.61	May	–0.62	Sep
Corylus avellana	Flowering	13–Apr	–0.61	Apr	–0.69	May	–0.61	May	–0.54	Jul
Betula pendula	Leaf unfolding	6–May	–0.77	Apr	–0.76	May	–0.66	Jun	–0.66	Jul
Acer platanoides	Begin of flowering	9–May	–0.86	Apr	–0.84	May	–0.74	Jun	–0.70	Jul
Prunus padus	Begin of flowering	17–May	–0.70	Apr	–0.80	Jun	–0.80	Jun	–0.68	Aug
Syringa vulgaris	Begin of flowering	26–May	–0.71	May	–0.83	Jun	–0.75	Jun	–0.61	Jul
Sorbus aucuparia	Begin of flowering	30–May	–0.72	May	–0.80	Jun	–0.73	Jun	–0.58	Aug
Tilia cordata	Begin of flowering	12–Jul	–0.58	May	–0.48	Jun	–0.52	Jul	–0.30	Aug
Ribes nigrum	Leaf fall	17–Oct	–0.38	Mar	–0.53	Aug	–0.61	Aug	–0.57	Oct
Secale cereale	End of veg.	27–Oct	–0.28	Aug	–0.17	Sep	–0.14	Sep	–0.10	Oct

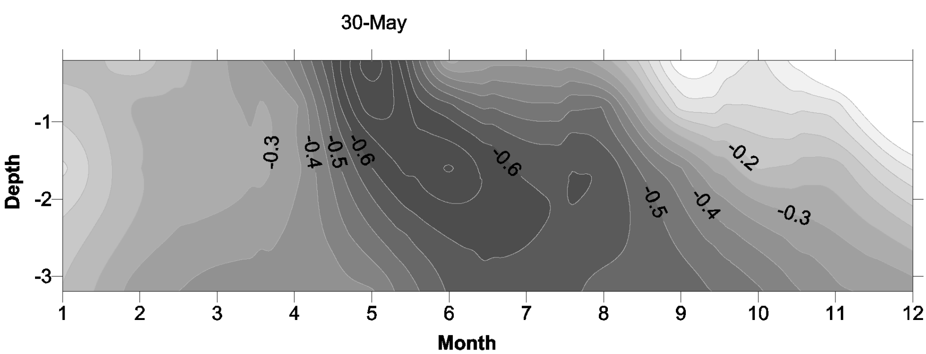

Figure 15. Distribution of the correlations between flowering of rowan (mean beginning date 30 May) and soil temperature at different depths in Võru 1954–1999.

Trends in temperature

Strong correlations between the studied phenological events and rises in temperature parameters are needed to describe trends in temperature. Temperature changes have been well studied in Estonia (Ahas and Aasa, 2003b; Jaagus, 2003; Jaagus, in press; Jaagus and Ahas, 1998) and Europe (IPCC, 2001). We do not focus on that, but by explanation we present some trend analysis results in the dataset we used for our phenological studies.

Climate change scenarios for Estonia based on the results of experiments with different general circulation models indicate a significant warming due to the increase of the greenhouse effect (Keevallik, 1998; Kont et al., 2002). An average increase in monthly mean air temperature of 2–4°C has been projected for the year 2100.

If we study changes in air temperature in Estonia and in Central Europe for the study period, 1951–2000, they show similar trends and spatial pattern to phenological phases. The monthly distribution of air temperature changes for Võru station in southeastern Estonia is shown in Figure 16. The changes are strongest in winter and early spring, from January to April. The trends in February and March have a significant value, and in March air temperature changed 5.2° C and was statistically significant at all Estonian stations.

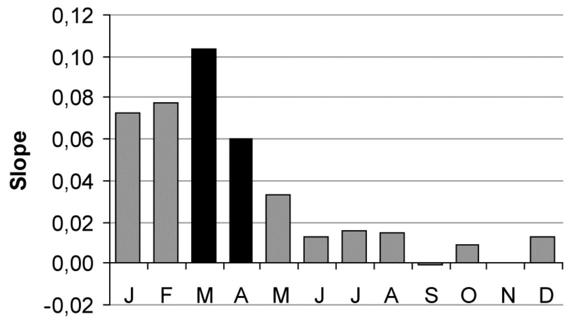

Figure 16. Changes of the air temperature in Võru station 1950–1999 (Black column = P<0.05).

The mapped changes in the length of the growing season in Estonia are presented in Figure 17. The changes are positive (lengthening) in western Estonian maritime areas, and there are significant trends in Kihnu Island and the Kõpu peninsula lasting 10–14 days. In Eastern Estonia the changes are smaller, and in some locations (Jõgeva, Kunda) are even negative.

Trends in soil temperature recorded at the Võru station are presented in Figure 18. The figure shows that changes are up to 5 degrees in April. This temperature change in April accumulates in deeper layers of the soil during spring and summer. There is noticeable trend towards temperature decreases in fall, and a similar tendency is visible in Estonian air temperature records, but the change is small and not significant.

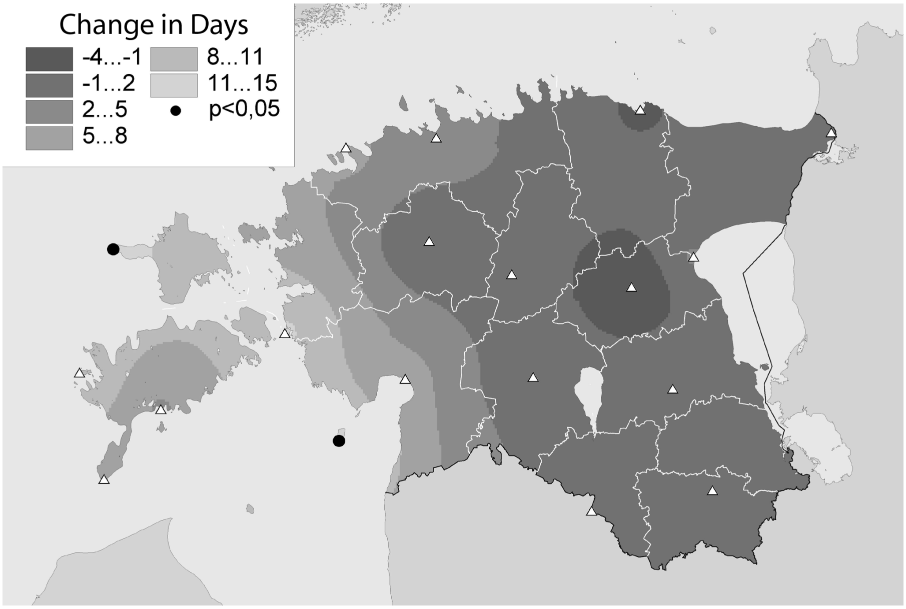

Figure 17. Trend in duration of growing season (period with mean daily air temperature over 5ºC) in Estonia.

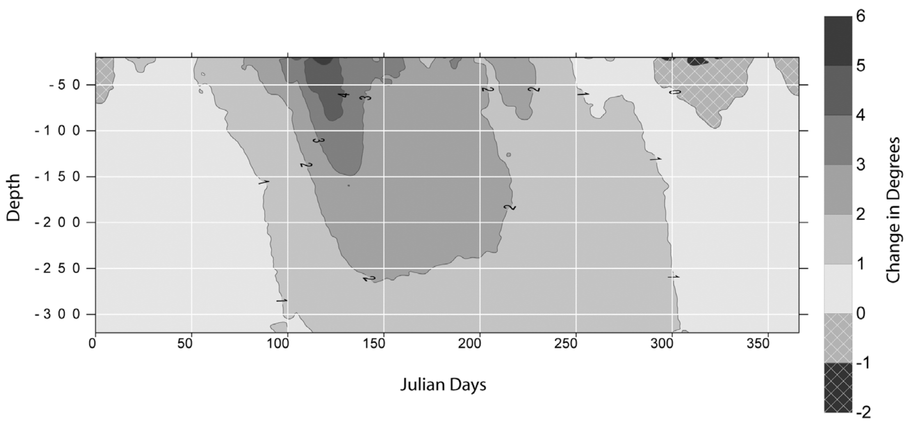

Figure 18. Changes of the soil temperature in Võru station 1954–1999.

6. CORRELATIONS WITH ATMOSPHERIC CIRCULATION

The temperature regime is generally determined by atmospheric circulation (Sepp and Jaagus, 2002). The analysis of the correlation between phenological phases – the flowering of coltsfoot (*Tussilago farfara* L.), the unfolding of birch leaves (*Betula pendula* Roth.), the flowering of lilac (*Syringa vulgaris* L.), and circulation patterns in Europe has shown that in the Baltic Sea region, spring phenology is primarily influenced by the NAO and AO indices during winter (December–March) and the first three months of the year (January–March). This was evidenced by a measured correlation stronger than –0.5 in the Baltic Sea region (Aasa et al., 2004).

Influence of winter circulation

The results of the correlation analysis demonstrate significant relationships between the parameters of large-scale atmospheric circulation and the start dates of the three phenological phases in Central and Eastern Europe. The first and the most important result is that atmospheric circulation during the previous winter is closely related to phenological phases during the following spring. This relationship is expressed most strongly in the case of early phases. The flowering of coltsfoot is determined most of all by the nature of the atmospheric circulation during the previous winter. As a general rule, a mild winter is followed by an early spring, and coltsfoot, which is quite an early flowerer, responds rapidly to this. Following a cold winter, the ground thaws more slowly, and the growth and development of plants is retarded.

Mild winters in central and eastern Europe are associated with a zonal circulation. A strong westerly airflow carries warm air from the Atlantic far towards the east. Zonal circulation indicators, NAO and AO indices, and the frequency of circulation forms W and the zonal circulation group (Z) are negatively correlated with the onset of flowering of coltsfoot (Figure 19). This means that flowering begins earlier following a mild winter and later following a cold winter.

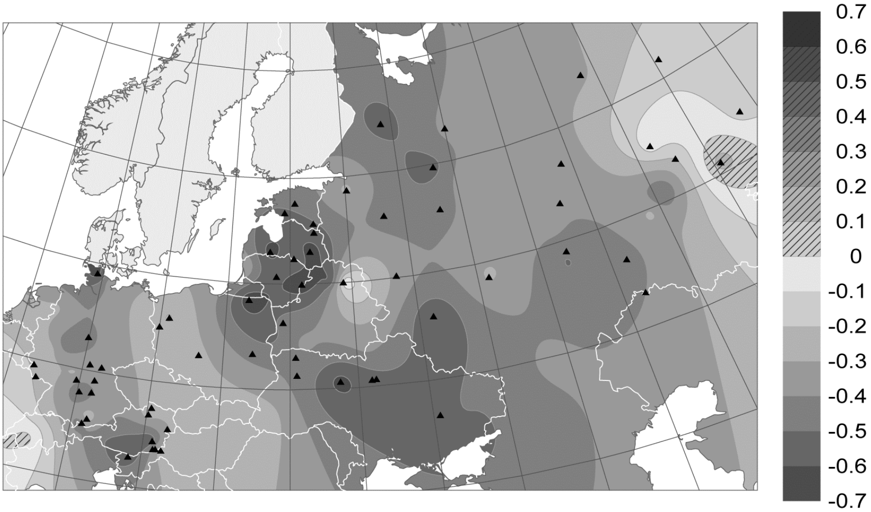

Figure 19. The spatial distribution of the correlation coefficients between the onset of flowering of coltsfoot and NAO_{JFM} (Aasa et al., 2004).

The beginning of the phase has the highest correlation with the NAO_{JFM} index, for which the correlation coefficient in the study area falls within the range –0.7 to 0.2. Approximately the same correlation pattern was also obtained for winter AO indices. The areas with higher correlation are the Baltic countries, Ukraine, northern Russia and some regions in Germany and Austria. The correlation of the onset of flowering of coltsfoot with the indices of individual months has a much greater spatial variance and is generally weaker than the correlation with the index averaged over several months.

A rather similar pattern is also present for frequencies of zonal circulation types W and Z. The negative correlation of the start date of flowering of coltsfoot with the frequency of the circulation form W is highest in northern Ukraine, and with zonal circulation group Z in central Europe ($r > |-0.6|$).

At the same time, the frequencies of meridional circulation types (E and M) in winter have a significant positive correlation with the beginning of the flowering of coltsfoot. These circulation parameters are closely related to the cold weather conditions in winter, to the prevailing cold continental air mass and extended anticyclones in northern Europe. Thus in Schleswig (54.52° N, 9.57° E) the correlation between the frequency in winter of the meridional type (M) and the onset of flowering of coltsfoot almost reaches the level of 0.7. Although the spatial variance of the correlation coefficient is large (–0.1 to 0.7), the correlation is higher than 0.5 at 15 observation stations. The semi-meridional circulation group in winter is negatively correlated with the flowering of coltsfoot, but the correlation is mostly low.

The influence of winter circulation is also evident in birch leaf unfolding and in the flowering of lilac, but to a lesser magnitude. The spatial pattern of the correlations has the same general distribution. The highest negative correlation coefficients, $r > |-0.6|$, are located in the Baltic Sea region. The frequency of meridional circulation group M, according to Hess and Brezowsky, has a high positive correlation with birch leaf unfolding. The maximum correlation is located in the East European Plain, and also in Poland, Germany and Austria. The influence of meridional circulation, i.e. cold winter, is also evident in the flowering of lilac, especially in central Europe and in the Baltic region.

Different correlations with phenophases are observed in Kuznetskoye. There is a significant positive correlation between the flowering of coltsfoot and the characteristics of zonal circulation, and a negative correlation with meridional circulation in February. There are no significant correlations at all in Kuznetskoye between birch leaf unfolding and the flowering of lilac and the parameters of atmospheric circulation. This can be explained by the fact that the circulation indices and classifications designed for Europe are not valid for describing atmospheric circulation in places located so far east. In mountainous areas, local conditions most likely play a very important role in climate formation.

Influence of spring circulation

Large-scale atmospheric circulation in spring influences the beginning of plants' phenological phases. The correlation between them is highest in the case of later phases. The flowering of coltsfoot has a significant correlation with circulation parameters until March. This phase is entirely dependent on winter conditions. However, birch leaf unfolding and the flowering of lilac have some remarkable relationships with circulation parameters in April, and even in May.

The correlation between westerlies and the unfolding of the birch leaf weakens from March onwards, and by April it has disappeared altogether. The main circulation factor in April is northerly airflow, which brings cold Arctic air to southern regions and retards the phenological development of nature. Northerly advection is described by the frequency of circulation form C. It has a close relationship with birch leaf unfolding in the East European Plain, especially in northern Russia (Figure 20).

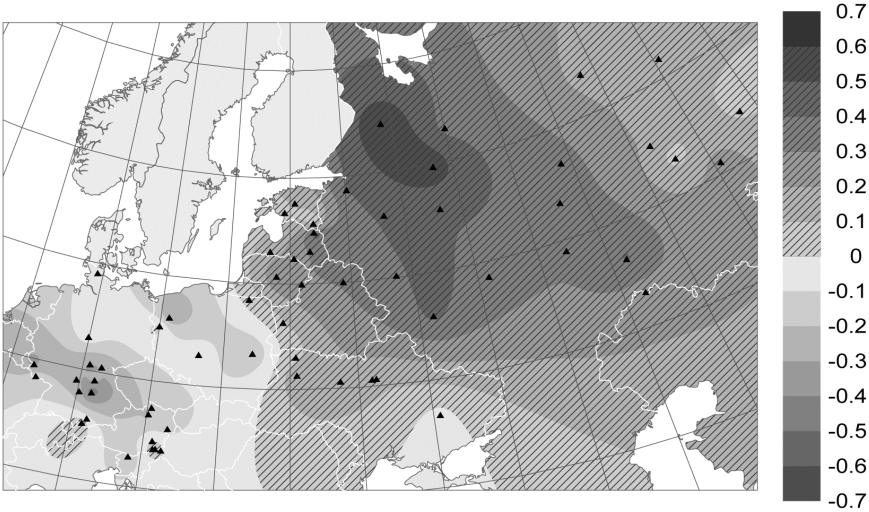

Figure 20. The spatial distribution of correlation coefficients between the beginning of birch leaf unfolding and C_{Apr} (Aasa et al., 2004).

The onset of flowering of lilac is directly influenced by spring (March–May) circulation patterns, with form E having the stronger correlation and more clearly defined spatial distribution. The greater the frequency of form E in spring, the later the onset of flowering of lilac in the western part of the study area. (Aasa et al., 2004)

Causes of phenological changes

The phenological development of plants is mostly driven by temperature in temperate zone (Chuine et al., 2003; Schwartz, 2003a). Therefore I assumed that those phenological changes detected in Estonia and Europe was caused by changes in temperature regime. The analyses show that daily mean air temperature has changed in Estonia in period 1951–1999 from January to May ($P<0.1$). Significant ($P<0.05$) warming trend has in March (5.2° warmer) and April (3.0° warmer) during study period as Estonian mean (Ahas and Aasa, 2003b; Jaagus, 2003). Most of climatologist connects changes in European spring temperature regime with significant changes in atmospheric circulation; especially North Atlantic Oscillation (NAO) during preceding winter and early spring period. NAO has changed in January, February and March significantly during last 50 years (Hurrell, 1995). There is significant correlation between J,F,M NAO and spring and summer phenology in Estonia and Europe (Aasa et al., 2004; Menzel and Sparks, 2005).

Correlations between NAO index, circulation indices, air temperature and phenology are significant during first half of year. Interesting aspect is that here is temporal lag between those parameters. NAO and circulation indices have significant changes during winter and early spring from January to March (Figure 21). Temperature, which is determined by winter NAO and circulation, has significant changes later, from January to May (Figure 16). The phenological phases, which are determined by air temperature changes during spring, have significant trends later, from April to August (Figure 22). Plant phenology has significant correlations with winter NAOI and relevant circulation indices till mid August, this was analysed in the chapter 6. As the circulation changes during winter and early spring influence phenology during following spring and summer this can be result of temperature inertia.

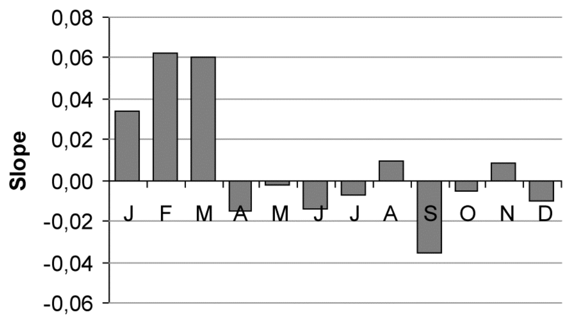

Figure 21. Slopes of monthly NAO index 1950–2000.

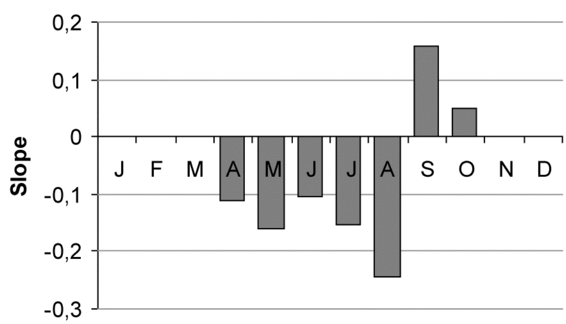

Figure 22. Average change of the phenological phases in Estonia 1951–1999.

Temperature can be accumulated in surface and water bodies and this can influence plants later. From this point of view is interesting to analyze impact of water bodies which have higher capacity to accumulate heat. The higher rate of phenological changes determined in chapter 4 can be related to this hypotheses.

The temperature accumulation in Baltic Sea can be so efficient because this area is under the direct influence of westerly air flow during winter and ice conditions can empower this effect. Ice conditions reflect mildness of winters in Baltic Sea and this has great effect on temperature regime and phenology in coastal areas (Jaagus et al., 2003). In Figure 23 is comparison of phenological trends in Estonian coastal station Pärnu and more continental area Võru. Võru trends are smaller and this tendency is also in air temperature and climatic seasons data (Jaagus and Ahas, 1998). The temperature accumulation is also presented in soil temperature data on chapter 5 and Figure 15.

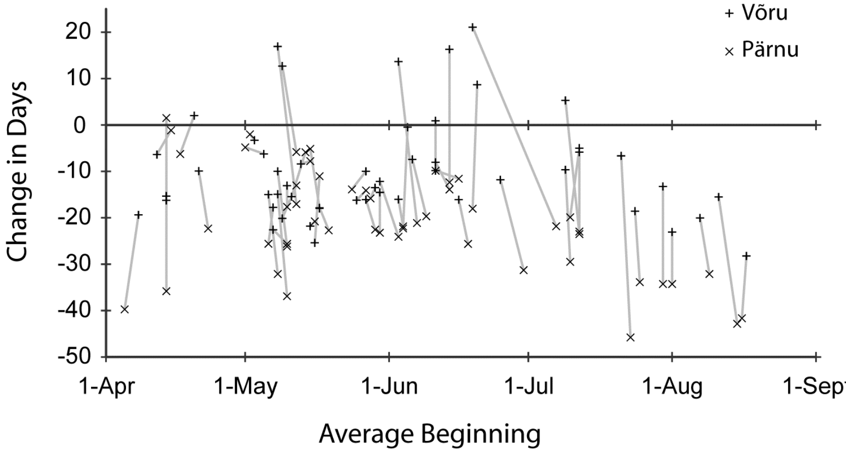

Figure 23. Comparison of trends in coastal station Pärnu and inland station Võru.

The temperature can be accumulated also by plants, it can be described with the so called thermal memory. It means that the entering to a certain development stage is dependent on the previous thermal regime of the plant (Chuine and Cour, 1999; Kramer et al., 1996; Lappalainen, 1994). The requirement for warmth differs both in species and in phases. There are also other factors playing role in the development of the plant e.g. daylight, wind, humidity, growing substrate etc. Due to the thermal memory, the phenological phases can be considered as good indicators reflecting the conditions of the previous growing season. The degree days are accumulated during spring and summer and have high correlations with phenological phases (Davitaja, 1964; Defila, 1991; Schnelle, 1955). Warmer winter and spring accumulates more degree days and plant development is influenced by this. There are other important aspects of this phenomenon: changes in winter temperature can influence winter dormancy conditions. Temperature regime of winter dormancy is influencing phenology during following spring and summer. The exact mechanisms of winter dormancy and negative temperature sums is very little studied (Chuine et al., 2003; Schwartz, 1997).

7. DISCUSSION

Phenological trends

We analysed phenological trends in Estonia and Central and Eastern Europe. Results showed that spring phenology has advanced significantly in Estonia and Central Europe during last 50 years (Aasa, 2001; Ahas, 1999; Ahas and Aasa, 2001; Ahas et al., 2000). Significant changes were detected in majority of Estonian phenophases from April to August with average rate –0.13 days per year. Studied trends have different values in different geographical regions in Europe, and the Baltic Sea region and Central Europe have the highest rate of changes (–0.3 to –0.4 days per year) during the spring period.

Other phenological analyses in Europe show similar results as our studies. Menzel and Fabian (1999) studied the length of the phenological growing season, determined by leaf unfolding and leaf fall of various tree species of IPG dataset. Their results showed that growing season was lengthened significantly during the period 1951 to 1996. On average, the spring arrival trend was negative (arriving earlier) and the autumn trend positive (arriving later) in Europe. The mean trend of the 616 spring phases studied over all Europe changed by –2 days per decade; the 178 fall phases changed by +1.6 days per decade during the study period. As a result, the average growing season was longer by 3.6 days per decade in the study area.

Chmielewski and Rötzer (2001) analysed changes in the phenological growing season for 1968–1998 with the IPG dataset for determined sub regions including the Baltic Sea Region which almost covers Estonia. They determined the beginning of the growing season by means of a combined leafing index (*Betula pubescens, Prunus avium, Sorbus aucuparia and Ribes alpinum*) and the end of the growing season by the mean leaf fall date of four species (*Betula pubescens, Prunus avium, Salix smithiana, Ribes alpinum*). There was a significant ($P<0.05$) lengthening of the growing season, by 2.7 days per decade over all Europe. However, in the Baltic Sea Region the trends were much stronger in most of the stations: the growing season lengthened by 4.5 days per decade, as the onset of spring shifted significantly earlier (Chmielewski and Rötzer, 2001).

Results of our trend studies show similar results and we can conclude this trend detection: seasonal development of spring phases has advanced during last 50 years significantly in Central Europe and especially in Baltic Sea region. If we study longer periods (all 20th century) the phenological and seasonal changes are smaller (Ahas, 1999). The studies of IPCC (IPCC, 2001) show that most significant changes in temperature parameters happened during last half century. Similar phenological trends were detected also in China (Chen et al., 2005) and North America (Schwartz and Reiter, 2000).

Phenology and pollution

According to the most common theory the climatic change has an anthropogenic nature. As a main factor of warming the emission of greenhouse gases is emphasized (IPCC, 2001). But the phenological phases can be also influenced by other determinants than changing climate as land use change, urban heat islands and environmental pollution. Those changes have been most considerable in urban areas, where the largest number of Earths human populations is living today (Jin et al., 2005). In areas with high human density (city's) an effect of Urban Heat Islands (UHI) is often registered. This is a phenomenon implicating that it is warmer in the city than in the surrounding rural areas. The mean annual temperature in urban areas is approximately 1–3°C higher than in the rural areas (Zhang et al., 2004), this causes also phenological differences.

For urban areas in northern hemisphere the onset of greenup is 4–9 days earlier on average and the onset of dormancy is about 2–16 later compared to the rural areas (Zhang et al., 2004). Analyses of the satellite data of North-America has proven that the urbanization is associated with the growing period expansion of 7.6 days in average compared to the rural areas. At the same time the greenup is 5.7 days earlier in average and the onset of dormancy is about 2.0 days later (White et al., 2002).

Studies of the UHIs in Central Europe have been proven that in 68% of the cases the phases appeared about 3–16 days earlier in cities compared to the rural areas. 22% of the trends were significant 1951–1995. The early spring phases shifted 14–15 days earlier for a decade; spring phases 7–9 days earlier for a decade. At the same time the trend of rural phases was stronger in 1980–1995 (Roetzer et al., 2000). The stronger trend of rural phases in Central Europe may be connected with increase of the influence of cities in the corresponding area: the influence of UHIs could even decrease in the situation of sustainable development or urban sprawl.

Predictions

Today we can measure changes in phenology that stay in limits of natural variability recorded during last 50 years (chapter 4). Interesting question is also future scenarios of climate change impacts on phenology. Calculation of the average effect of climate warming shows that a rise in mean temperature by 1°C will lengthen the phenological growing season by 5 days in temperate Europe (Chmielewski and Rötzer, 2001). Model predictions based on increasing CO_2 concentration and Global Circulation Model showed that snowdrop (*Galanthus nivalis*) flowering will occur 2 weeks earlier if CO_2 concentration doubles by

2035 and one month earlier if CO_2 triples by 2085 in Northern Germany (Maak and Storch, 1997).

The scenarios of +2°C and –2°C temperature rise used in the Estonian analysis showed that in these cases the phenological development of nature remains within the limits of natural variation (Ahas et al., 2000). The case of a 4°C warmer spring has also been studied, with the results showing that the common spring phases will still remain within the limits of the extreme years studied, such as 1975, 1989, 1990 (Ahas et al., 2000). Several authors have pointed out that the phenological development of nature is relatively flexible since many species and their phenological varieties adapt to the natural variations of spring in temperate regions. However, many phenological models predict that global warming and earlier springs will result in increased risk of frost damage for species all over Europe. The Linkosalo (Linkosalo et al., 2000) studied frost damage risks with a chill-triggered model in Finland and results showed that increased frost risks would occur during earlier (warmer) springs in Finland. The light-climate-triggered model did not however prognoses those risks (Linkosalo et al., 2000). Statistical analysis of *POSITIVE* data showed that the risk of late frost damage for plants during spring in Central Europe have been lower during the last decade compared to the previous decades (Scheifinger et al., 2003).

8. CONCLUSIONS

The current dissertation studied phenological trends in Estonia and Central Europe and analyzed the causes of the recorded phenological changes. Phenological data from different datasets showed similar results: spring and summer phases have advanced remarkably in Estonia and Central and Eastern Europe. Phases in the spring period have shifted –0.2 to –0.4 days and in the summer period –0.2 to –0.3 days earlier per year during last 50 years. The highest rate of changes is recorded in the Baltic Sea region and Germany. This phenological change is significant in most of these locations and the impact of the changing climate is visible.

Phenological trends recorded can be explained by changes in air (and soil) temperature, which is significant during the spring in most of the study area. In Estonia spring temperatures (monthly mean) have changed from January to May by 0.02–0.10 degrees higher per year. Significant changes have been recorded during February and March. Phenology and air temperature are influenced by changes in atmospheric circulation during winter. Our analysis showed that the majority of spring phases in Central and Eastern Europe have a significant correlation with winter circulation indices (westerly flows) with correlation coefficients up to |0.7|. Also the summer phenology has a significant correlation with winter circulation indices. Our study shows that a changing winter temperature regime influences the following spring and summer via temperature inertia in the environment (soil, water) and by temperature accumulation by plants. This temperature accumulation in plants is known as heat requirement and is measured by cumulative temperature sums.

There is need to further analyze the effects of winter dormancy, as changing winter weather can influence plant phenology during the following spring and summer also directly, not by heat accumulation. For example, the changing temperature or air pressure of snow cover can influence winter dormancy and activate a biological regulation, which can influence phenological development in the spring or summer. This and many other aspects of the impact of climate change on plant phenology needs to be studied with historical databases or experimental studies which are becoming more and more common in phenology.

9. SUMMARY IN ESTONIAN

Muutused fenoloogilistes aegridades Eestis ning Kesk- ja Ida-Euroopas 1951–1998. Seosed õhutemperatuuri ja atmosfääri tsirkulatsiooniga

Looduse aastaajalisi arenguetappe kirjeldavad fenoloogilised faasid on headeks keskkonnaseisundi indikaatoriteks. Tänu lihtsale vaadeldavusele on käeolevaks ajaks talletatud suur hulk fenoloogilist andmestikku. Viimasel ajal on fenoloogilise uurimistöö üheks juhtivaks suunaks tõusnud globaalsete muutuste kirjeldamine.

Käesoleva töö eesmärgiks on 1) teha kokkuvõte Eesti ning Kesk- ja Ida-Euroopa taimefenoloogilistest muutustest perioodil 1951–1999; 2) uurida fenoloogiliste muutuste seoseid muutuva kliima parameetritega nagu õhu- ja mullatemperatuur ning atmosfääri üldine tsirkulatsioon.

Töös on kasutatud EMHI ja *POSITIVE* fenoloogilisi andmebaase. Käsitletav ala hõlmab Kesk- ja Ida-Euroopat Saksa läänepiirist Uuraliteni ning Põhja-Venemaast Lõuna-Ukrainani. Õhu- ja mullatemperatuuride aegread on pärit EMHI vaatlusvõrgust. Seoseid atmosfääri üldise tsirkulatsiooniga uuriti kahe indeksi (NAOI, AOI) ja kahe klassifikatsiooni abil (Grosswetterlagen, Vangengeim-Girs).

Analüüsitulemustest selgub, et *ca* 50% fenoloogilise faasi algus on nihkunud oluliselt varasemaks. Seejuures on suuremad muutused täheldatavad uuritava ala Läänemere piirkonnas. Fenoloogiliste nähtuste alguse ja kliimakarakteristikute vahel on tugevad seosed: mida soojem on mingile faasile eelnev periood, seda varasemaks vastava faasi algus muutub. Fenofaaside alguse ja õhu- ning mullatemperatuuri vahelisel korrelatsioonanalüüsil ulatus tugevamate seoste korrelatsioonikordaja R tasemeni 0,8. Ka atmosfääri üldise tsirkulatsiooniga on fenoloogilistel faasidel statistiliselt olulised seosed. Seoste tugevus on varieeruv nii indeksite/klassifikatsioonide kaupa kui ka piirkonniti. Kõige tugevamad on seosed läänevoolu kirjeldavate tsirkulatsiooninäitajatega.

Atmosfääri tsirkulatsiooni ja fenofaaside alguse vahelised seosed on eelkõige kaudse iseloomuga, kuna tsirkulatsiooni iseloom dikteerib eelkõige kohalikku soojarežiimi ja avaldub alles läbi temperatuurimõjude taimede arengus.

Klimaatiliste ja fenoloogiliste muutuste kõrvutamisel ilmneb, et kui klimaatilised karakteristikud näitavad soojenemise tendentsi talvisel ning kevadisel perioodil, siis fenofaaside algus on muutunud varasemaks kõige rohkem kevadel, kuid olulised muutused on täheldatavad ka järgneva kasvuperioodi vältel. Selle põhjustajaks on asjaolu, et taimede erinevad arenguetapid on omavahel seotud, st et mingi taime varasem fenofaasi algus tingib ka kalendaarselt järgmiste faaside varasemaks nihkumise.

Suuremate fenoloogiliste muutuste piirkond (Läänemere regioon) kattub alaga, kus on kõige tugevamad seosed läänevoolu intensiivsust kirjeldavate tsirkulatsiooninäitajatega. Läänevoolu intensiivistumist on peetud üheks peamiseks Euroopa kliima soojendajaks.

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THE EFFECTS OF CLIMATE CHANGE ON THE PHENOLOGY OF SELECTED ESTONIAN PLANT, BIRD AND FISH POPULATIONS

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ABSTRACT

The paper summarises the trends of 943 phyto-, ornitho- and ichthyophenological time series gathered from 1948–1999 in Estonia. More than 80% of the studied phenological phases have advanced during springtime, whereas changes are smaller during summer and fall. Significant values of phytophenological and ornithophenological phases have advanced 5–20 days, and ichtyophenological phases have advanced 10–30 days in the spring period. Estonia's average air temperature has become significantly warmer in spring, while at the same time a slight decrease in air temperature has been detected in autumn. The growing season has become significantly longer in the maritime climate area of Western Estonia. The investigated phenological and climate trends are primarily related to changes in the North Atlantic Oscillation Index (NAOI) during the winter months. Although the impact of winter NAOI on the phases decreases towards summer, the trends of the investigated phases remain high. Those trends of phenophases at the end of spring and the beginning of summer may be caused by the temperature inertia of changing winter, changes in the radiation balance or the direct consequences of human impacts such as land use, heat islands or air pollution.

Keywords: Phenology, phythophenology, ornithophenology, ichthyophenology, air temperature, climate change, phenological trends, global warming, Estonia

INTRODUCTION

Phenological phases are important indicators for detecting the impact of changing climate on organisms and ecosystems, as they reflect the complicated combination of environmental changes in visually measurable form. Because of this, the phenological time series have been observed during recent centuries, and can today be used as valuable sources for the investigation of climate change. The data of phenological observations have been systematically recorded in many countries and international networks. The Estonian phenological data set has long time series, a good selection of observed species and very good spatial coverage. Over a number of years, the Estonian Naturalists' Society (ENS), the Estonian Meteorological and Hydrological Institute (EMHI) and the Estonian Ornithological Society (EOS) have compiled a valuable phenological database consisting of data on the phenology of plants, birds, fishes, mammals, insects and mushrooms. This data has been used in different studies of the impact of climate changes.

Estonian phenological studies show that spring has advanced significantly, and winter has become shorter (Aasa, 2001; Ahas, 1999; Ahas, 2001; Ahas et al., 2000), while other seasons have not undergone many significant changes. This contributes to phenological studies in Europe (Ahas et al., 2002; Chmielewski and Rötzer, 2001; Fabian and Menzel, 1999; Menzel, 2000; Menzel and Estrella, 2001; Menzel and Fabian, 1999) and other regions (Beaubien and Freeland, 2000; Chen et al., 2000; Parmesan and Yohe, 2003; Sparks and Braslavska, 2001), that also report significant changes in the seasonal development of nature. Trends have different values in different geographical regions, and the Baltic Sea region and Western Europe have the highest rate of changes during the spring period. For example, the unfolding of birch leaves and the flowering of hazel and lilac have advanced by an average of 2–4 weeks in Europe, and most of these trends have significant values. Similar trends have been recorded in North America, where the most significant changes in spring phenology have been recorded in eastern and western regions (Schwartz and Reiter, 2000).

The aim of the current study is to summarize the phenological trends recorded in different observation networks over the last half century in Estonia, and to relate the analyzed trends to changes in regional climate. This work complements our earlier study of phenological trends in Estonia (Ahas, 1999), after the investigation of all important phenological databases in Estonia.

1. MATERIALS AND METHODS

We have gathered and evaluated the majority of Estonia's systematically recorded phyto-, ornitho-, and ichtyophenological time-series into one database. Figure 1 shows the location of Estonia in Europe and the spatial distribution of the observation sites, Figure 2 the temporal distribution and standard deviation of the investigated phases. The minimal length of 35 years of the observation series during the period 1948–1999 is the main criterion for phyto- and ornithophenological time-series to be suitable for analysis. The number of observed years for the ichthyophenological time series was only 25, because of more fragmented observation data in that area (Table 1).

In this study we use the term time-series to describe data that has been recorded for: one development phase (e.g. beginning of flowering) of one species (example: lilac) observed at one observation station (e.g. Tartu). The data conform to normal distribution, and linear regression analysis was used to evaluate the direction and power of changes.

Phytophenological data come from the EMHI observation programme, which covers the time period 1951–1999 at 15 observation stations. In total, 753 time-series (one phase of one species observed in one station) of trees and bushes (409), fruit trees and berry bushes (185), field crops (220), potatoes (75) and grasses (49) have been used.

In addition to linear trend analysis, the phytophenological dataset was analysed using the method of advanced (early) and delayed (late) years. Early and late years were determined, counted and summarised on the basis of phases which started earlier or later than in the range of 1 standard deviation (Ahas and Aasa, 2003). Võru, Pärnu, and Türi stations, which have homogenous data, were selected for this analysis (Fig. 1). Categorisation into early or late season was based on mean values. The number of values out of ±1 standard deviation range is the simplest criteria for determining the phenological type of years. This value, presented as a percentage, is crucial for generalizing from phenological calendars, and determining the percentage of the total list of phases that were earlier or later than 1 standard deviation. The absence of identical data (differences in the list of phases and gaps) does not facilitate comparing years and places using simple methods (Ahas and Aasa, 2003).

The ornithophenological data (1948–1996) originates from the ENS observation programme. The data was evaluated and edited by I. and L. Rootsmäe, and has been published in the ENS series: A Guide for Nature Observers (Lint et al., 1963; Rootsmäe and Rootsmäe, 1972, 1974, 1976, 1978, 1981; Rootsmäe 1991, 1998). The spring arrival dates for selected common bird species – the white wagtail (*Motacilla alba*), Eurasian skylark (*Alauda arvensis*), chaffinch (*Fringilla coelebs*), barn swallow (*Hirundo rustica*) and lapwing (*Vanellus vanellus*) – were selected for analysis, due to the fact that these are the best observed phases. All in all, 157 time-series in 39 observation stations have been used in the current study.

The ichthyophenological observation data (1951–1998) originate from the ENS observation programme. The data were evaluated and generalised by J. Ristkok, and have been published in the ELUS series: A Guide for Nature Observers (Ristkok 1961–1993).

The database used in this study consists of about 20% of interpolated gaps. To fill in the gaps in the phenological time-series, the interpolation method based on the best correlations has been used (Ahas and Aasa, 2003), with the following steps. From the correlation matrixes of all time series, we selected those with the highest correlations. The selection was finalised among those with high correlations, by selecting the best time-series, using criteria of temporally close phase at the same station or the same phase at the geographically closest station. Then the mean interval between the observed dates of two time-series was calculated. Finally, the gaps were replaced with dates calculated on the basis of mean interval and real observation in selected time-series.

Interpolation was carried out separately for birds, fishes and plants. For ornitho- and phythopehnological data, the minimal criterion was 35 observations during the investigated period. The ichthyophenological database is more fragmented, and a minimum of 25 years of observations was used for the selection of time series. Therefore all the gaps in the ichthyophenological time series were interpolated with data on hydrological seasons at the closest station in the same the lake or river. Hydrological seasons were determined at the Institute of Geography of the University of Tartu for the same study period on the basis of threshold crossings of mean water temperature in the surface layer (Järvet, 2001). In total, 33 time-series from Vagula, Vilusi, Sindi and Tori observation stations were used for analysis.

Diurnal air temperature data come from 19 EMHI weather stations during the period 1951–1999. The growing season is defined as the period in which daily mean temperature was permanently above 5ºC at 19 weather stations from 1951–1999 (Jaagus, 2001; Jaagus and Ahas, 2000).

For the investigation of the causes of the phenological trends, we used the following characteristics of Estonian air temperature: monthly mean temperatures, the permanent crossing of daily mean temperature thresholds (0°C, 5°C, 10°C, 15°C), dates of reaching effective and active sums of temperatures (100°C, 200°C, 500°C), monthly sums of active temperatures, sums of negative temperatures of the previous winter. In calculating effective temperatures, mean daily temperatures higher than 5ºC are summed, and 5ºC is subtracted from every value. In calculating active temperatures, mean daily temperatures, higher than 10°C are summed. Connections with atmospheric circulation were investigated using the NAO index (Hurrell, 1995); both monthly and seasonal indexes (Dec–Feb, Jan–Mar, etc) were used. The circulation indices such as NAOI influence plants via temperature changes caused by atmospheric circulation (Aasa et al 2004). As a result of pre-analysis with all of these parameters, we selected four factors with the highest correlation with spring phenology for detailed correlation analysis: mean daily air temperature rise over 0º; date of reaching active sums of temperatures amounting to 200º; the sum of effective temperatures in April; $NAO_{Jan–Mar}$ index.

2. RESULTS

2.1. Phytophenological trends

There have been remarkable changes in the beginning dates of phytophenological phases in Estonia. The results of linear regression analysis show that 85.5% of (644) phytophenological time-series have advanced (Fig. 3), and the majority of them occur in spring. Statistically significant trends show that 138 time-series have advanced 10…15 days; 112 time-series 5…10 days and 53 time-series 15…20 days during the 49 years investigated. The 32 time-series that advanced more than 20 days are all statistically significant ($p<0.05$). 151 time-series have advanced 0…5 days, but the trends are not significant. 14.5% of phytophenological time-series have been delayed, and 20 of them have a statistically significant trend with a delay of 10…30 days. Delayed time-series that have significant trends are mostly autumn phases like the ripening of fruit and the colouring and falling of leaves.

Figure 4 shows the sum of spring phases in Pärnu station that occur earlier or later than ±1 standard deviation. The analysis of early/late years enables one to follow the annual variability of phenology more precisely than the slopes and significances of the linear regression model. Results show that in the beginning of the period (1950s) there are more delayed phases, reaching its peak in 1955 with 87 delayed phases. The number of delayed time-series decreases from 1955 to 1995. Years that are earlier than 1 standard deviation begin to dominate after 1980, reaching a peak in 1989, with 77 advanced phases. 1990, 1991, 1992 and 1993 also have a majority of advanced time series. The investigation of early and late years shows the occurrence of a decennial cycle in the phenological data, which has a correlation with the 8-year quasi-oscillation cycle of the NAOI (Greatbatch, 2000; Jevrejeva and Moore, 2001).

The spatial distribution of phenological trends shows that the western-Estonian maritime climate has advanced more than in continental inland areas and in northern Estonia. For example, the ear of rye has advanced 10…12 days in western Estonia, and 2…4 days in eastern Estonia. It is important to remember that in many cases the spatial differences in phenology in Estonia are smaller than those resulting from local natural peculiarities such as microclimate, relief, soil, observation errors etc. (Ahas and Aasa, 2001).

2.2 Changes in the arrival of migratory birds

The arrival dates of the Eurasian skylark, white wagtail, barn swallow, chaffinch and lapwing in spring have advanced remarkably, but the majority of trends are not statistically significant. Statistically significant changes show that 15 time-series have advanced 5…10 days, and 12 time-series 10…15 days (Fig. 5). The investigated database shows that birds whose arrival date is earlier in spring have the greatest trends. For example, the most significant changes occurred in the arrival of the Eurasian skylark and lapwing.

Most of the ornithophenological time-series, which have advanced 0…5 and 5…10 days, are not statistically significant. 20 ornithophenological phases have been delayed up to 10 days; the arrival dates of the barn swallow in some stations in eastern and southern Estonia have undergone statistically significant shifts towards later dates.

The arrival trends of the Eurasian skylark (Fig. 6) demonstrate a clear spatial distribution: in southern Estonia they have advanced 6…14 days, which is a significant change, whereas in northern Estonia the changes are smaller, in the range of 0…–8, and the trends are not significant. The spatial distribution of trends similar to the Eurasian skylark is also noticeable in the arrival of the lapwing and white wagtail. The change in the arrival time of the chaffinch is greater and more reliable on the western coast; the arrival trends of the barn swallow do not demonstrate clear spatial regularity.

2.3 Ichthyophenological trends

Changes in the phenological phases describing events in the life cycle of fishes are relatively smaller than changes in phyto- and ornithophenological time-series. In the case of fish phases, statistically significant changes can only be found among the advanced phases (Fig. 7). Four ichthyophenological phases have advanced reliably: the end of the first pike spawn in Vagula Lake have advanced 12 days, the end of the ruff spawn in Vilusi 28 days, the end of the first bream spawn in Vilusi 26 days and the migration of local smelt in Vilusi 19 days. In general, the majority of trends are not statistically significant, and their slopes are evenly divided between advancing and delaying.

In the case of ichthyophenological phases, spatial regularities have not been detected (Ristkok, 1974), as the distribution of observation stations is fragmented, and small lakes and rivers and big lakes and rivers have very diverse hydrological regimes and phenologies. The space-time dynamics of these hydrological phenomena have been investigated in different studies (Järvet, 2001). Results show that the greatest changes that can affect fishes are connected with earlier snow melting and floods. In Estonia the snow disappears 1–2 months earlier during late winter and early spring, and as a result there are fewer spring floods, which are important for the migration and spawning of many fish species.

2.4 Changing air temperature and growing season

In order to explain the phenological trends investigated, the trends of daily mean air temperature and the length of the growing season were analysed. Figure 8 shows trends in daily mean air temperature in Türi in central Estonia. The daily mean temperature rises remarkably in the first part of the year, i.e. from January to May, with significant trends from February to April. The trends in air temperature are similar in all of the weather stations in Estonia. The greatest spatial differences in the distribution of trends occur in March. In terms of the territorial distribution of trends, a south-eastern and north-western direction can be distinguished. The mean temperature in March rose most in Tartu (5.5ºC), and least in Tallinn (3.9ºC). Of western Estonian stations, in May the temperature only rose significantly in Kuressaare (1.7ºC) and in Pärnu (2.0ºC).

In July, August and September, the changes in daily mean temperature are less than 1ºC. From September to December, there are weak negative changes, with a value of up to –1 degree. A drop in autumn temperature has been mapped more in the north-eastern stations in Estonia, but these changes are minimal, and are not statistically significant.

The growing season has increased 6…15 days on the western coast and islands of Estonia (Fig. 9). The changes have significant trends in Ristna (13 days longer) and Kihnu (15 days longer). Those stations are located on the coastline of the Baltic Sea, which has a maritime meso- and microclimate. On the mainland of Estonia the length of the growing season has remained almost constant or become insignificantly shorter in a few stations. The same tendencies can be detected in respect to the duration of summer, which is determined by a diurnal temperature higher than 13ºC (Jaagus and Ahas, 2000).

3. CORRELATIONS BETWEEN PHENOLOGICAL TRENDS AND CHANGING CLIMATE

The investigated climate factors demonstrate a strong trend towards warming, mainly in winter and springtime, which decreases since the end of June. For example, the date on which mean air temperature exceeds 0ºC has advanced by up to 25 days, and the date of exceeding 15ºC has not changed. Geographically, the warming of mean air temperature during the spring period is higher in inland and southern Estonia, while on the other hand, the growing season is significantly longer on the islands of western Estonia (Fig. 9). In analysing correlations, it became evident that phytophenological phases correlate better with air temperature, ornithophenological phases with NAOI, and fish phases have weaker correlations with the above-mentioned parameters.

3.1. Correlations between phytophenological trends and climatic parameters

Correlation curves between the investigated phenophases and climatic factors are given in figure 10. The NAO of the first three months of the year has a strong influence on the development of plants in early spring. The strongest trend among the early spring phases is characteristic of the beginning of birch sap bleeding. This phase has strong correlations with climatic parameters during winter. For example, the correlation coefficient of birch sap bleeding is up to 0.9 when mean daily temperature permanently exceeds 0ºC; –0.8 with the NAO index of February and –0.7 with mean February temperature.

The impact of NAO decreases as spring advances. At the end of May and the beginning of June there is a definite increase in correlations between the investigated time series and NAOI. From the middle of June, the impact of NAO on the phenological phases of nature is small. The date at which permanent air temperature over 0ºC is reached has a similar but inverse correlation with NAOI, and decreases towards summer. Correlations of date of reaching the sum of active temperatures (the most typical of these, 200ºC, is given in Figure 10) increase during spring, and reach their peak by the end of May, after which the correlation between development phases and the sum of temperatures decreases abruptly. A similar correlation curve (with a small time drift) is also characteristic of the sums of effective temperatures of April and May, and also the dates of reaching a permanent temperature of over 5ºC and 10ºC, and the mean temperatures of April and May.

The correlation curves of phenological phases given in Figure 10 indicates that the impact of NAO on the phases is highest in early spring, but later the impact decreases. The NAOI of January-March has the strongest impact on phytophenological phases. The time series and trends of birch sap bleeding and the flowering of rowan trees are given in Figure 11 in the background of NAOI values. The correlation of birch sap bleeding with the mean value of NAOI in the January-March index is –0.8, and the correlation of rowan flowering two months later is –0.5. The beginning of birch sap bleeding and the flowering of the rowan has become significantly earlier during the period investigated, 25 and 13 days respectively. As a result, it is important to study the space-time variability of NAOI impact on phenological phases in greater detail.

3.2. The correlations between ornitho- and ichtyophenological phases and climate parameters

The arrival time of migratory birds is not only influenced by natural conditions at the arrival spot, but also by conditions in the wintering area and along the migration route. Apparently the arrival times of birds therefore have a stronger correlation with circulation indexes than with local weather parameters such as air temperature. Circulation indexes like NAOI describe the weather conditions of larger areas. The correlation of the arrival times of 5 studied migratory bird species with the NAO index is higher in early spring and decreases as spring advances. For example: the correlation of the average date of skylark arrival on 23 March with NAOI is highest in March (r = –0.75); the correlation of the average date of barn swallow arrival on 2 May with the NAOI of April is only –0.4. Birds' arrival also has a relevantly strong connection with the date at which air temperature rises above 0ºC.

In comparison to other correlations, the phenophases of fishes generally have smaller correlations with the investigated climate parameters. Phases that begin at the end of March and April have a relevantly strong connection with mean temperature in February and March, for example the correlation between smelt spawning and mean temperature in February is –0.8. It has been noted that phases occurring in May, such as the spawning of bream and the end of roach spawning, have relevantly weak connections with the investigated climatic factors.

4. DISCUSSION AND CONCLUSIONS

According to the study, the main changes in the seasonal development of Estonian nature have taken place in spring. This tendency is significant, even in spite of the fact that there has been more observation of phases during spring. In this paper, a total of 943 time series and 65 the external environment parameters have been analysed. In phytophenological and ornithophenological time series, most of the significant changes have advanced 5–20 days, and in the case of ichthyophenological phases, they have advanced 10–30 days. All environment parameters calculated on the basis of air temperature demonstrate a warming trend in spring, and the vegetation period has increased in western Estonia.

Several authors (Aasa et al.,2004; Menzel, 2003; Scheifinger et al., 2002) relate phenological trends in Europe with changes in NAO. There are relevantly strong correlations between NAOI (especially mean of January to March) and phenological time series, which have strong trends. In the case of a high NAOI value, the warmer air masses in winter and early spring arrive in Estonia from the Atlantic Ocean. As a result, winter ends earlier and spring begins earlier. This has a significant impact on the phenophases of early spring, which have relevantly high correlations with NAOI. The impact of NAOI decreases as spring advances, and correlations also decrease. At the same time, trends in phenological time series and investigated climatic factors remain high. There has not yet been any success in finding a conclusive explanation for trends in the Baltic Sea region (including Estonia) at the end of spring and the beginning of summer. There are other types of air masses from the east than NAOI (Aasa et al., 2004) that predominate in April and May in the Baltic Sea region, but no trends in the frequency of their occurrence have been detected. One reason for those trends in late spring and the beginning of summer may be the temperature inertia of a warmer winter and spring. No other circulation coefficient studied in the spring-summer period in Middle and Eastern Europe gives correlations similar to NAOI (Aasa et al., 2004; Jaagus et al., 2003).

If phenological trends in spring and summer are related to changes of NAOI in winter, then what is the mechanism? There might be temperature inertia in soil and water that can be transmitted with the accumulating temperature degree-days. The sums of those degree-days sums, which are accompanied by changes in early spring, can influence the entire growing season. Another mechanism may be related to the earlier melting of snow, which may make the soil dryer and facilitate a faster increase in temperature. Another possible explanation is connected with registered changes in atmospheric radiation in Estonia and Europe (Wild et al 2005). The recently published observations show that solar radiation in Estonia has become more intense since 1990, because of changes in air pollution during the post-Soviet period and changes in atmospheric circulation. This may also have an important impact on spring phenology, which has advanced during the same period.

These questions could apparently be answered after more detailed analysis of the data, which will dissect correlations of different phenophases and climatic factors, and their variation during years with early and late springs. The analysis of geographical differences in Estonia or Europe could be of significant importance to the attribution of phenological trends. This approach requires the detailed investigation of other natural conditions (such as soil, landscape, land cover, vegetation type, etc.) at all observation stations.

Changes in local climate and phenology may also be caused by the direct and indirect impact of human activities. The investigation of the impact of human activity is complicated, as present databases are not perfect, and natural variability in phenological time series is much greater than the direct impact of human activities. In phenology the impact of heat islands has been studied on the basis of German and USA data (Roetzer et al., 2000; White et al., 2002). The impact of changed land use and pollution has been studied to a lesser extent, but may offer new knowledge for the explanation of phenological trends.

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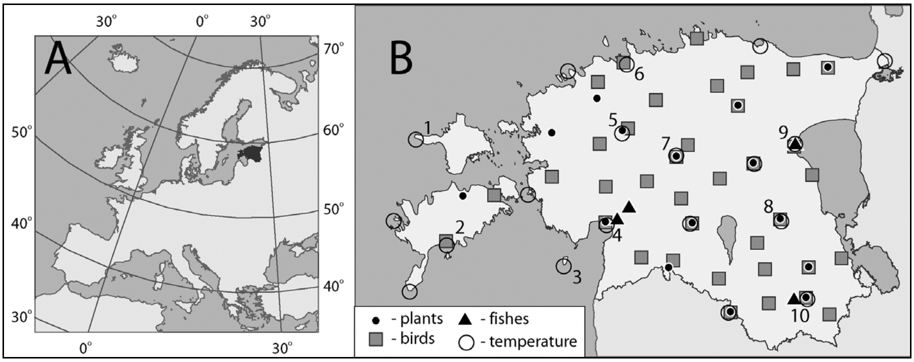
Species	Phase	Average beginning	Change in Days	Number of Observation Series
Lota lota	Spawning	27–Jan	–2,3	2
Perca fluviatilis	Appearance	9–Apr	–3,3	2
Esoc lucius	Spawning	16–Apr	–2,9	4
Osmerus eperlanus eperlanus	Spawning	17–Apr	–2,2	2
Gymnocephalus cernuus	Appearance	28–Apr	7,1	2
Osmerus eperlanus eperlanus morpha spirinchus	Spawning	6–May	–5,1	2
Perca fluviatilis	Spawning	12–May	1,7	2
Gymnocephalus cernuus	Spawning	15–May	–19,7	2
Leuciscus cephalus	Spawning	20–May	–6,2	2
Abramis brama	Spawning	28–May	–2,6	6
Alauda arvensis	Arrival	23–Mar	–9,0	35
Vanellus vanellus	Arrival	26–Mar	–5,4	31
Motacilla alba	Arrival	7–Apr	–3,6	33
Fringilla coelebs	Arrival	27–Apr	–5,2	29
Hirundo rustica	Arrival	3–May	–0,6	31
Betula pendula	Sap bleeding	6–Apr	–15,0	11
Alnus	Flowering	10–Apr	–7,6	6
Corylus avellana	Flowering	13–Apr	–7,6	7
Secale cereale	Begin of Vegetation	14–Apr	–1,3	11
Ribes nigrum	Bud burst	16–Apr	–7,8	10
Malus domestica	Bud burst	26–Apr	–3,5	30
Ribes rubrum	Bud burst	30–Apr	–2,5	9
Prunus padus	Foliation	7–May	–12,1	10
Secale cereale	Spear	7–May	–5,2	21
Betula pendula	Foliation	8–May	–13,0	13
Sorbus aucuparia	Foliation	10–May	–12,5	8
Acer platanoides	Flowering	11–May	–7,2	9
Betula pendula	Flowering	11–May	–4,5	12
Tilia cordata	Foliation	16–May	–7,1	9
Prunus padus	Flowering	19–May	–7,7	11
Ribes nigrum	Flowering	21–May	–10,4	10
Syringa vulgaris	Flowering	30–May	–8,6	10
Malus domestica	Flowering	30–May	–7,2	35
Hordeum sativum	3rd leaf	31–May	–6,1	15
Sorbus aucuparia	Flowering	31–May	–8,1	9
Secale cereale	Ear formation	3–Jun	–6,5	11
Hordeum sativum	Sprout	6–Jun	–3,4	14
Hordeum sativum	Spear	10–Jun	–2,8	15
Solanum tuberosum	Emergence	17–Jun	–10,0	15
Secale cereale	Flowering	19–Jun	–5,0	11
Hordeum sativum	Ear formation	3–Jul	–4,9	10

Tilia cordata	Flowering	12–Jul	–7,8	9
Secale cereale	Ripeness	21–Jul	–5,4	22
Solanum tuberosum	Flowering	25–Jul	–13,0	45
Hordeum sativum	Ripeness	30–Jul	–8,0	30
Avena sativa	Ripeness	9–Aug	–11,0	8
Malus domestica	Autumn colouring	4–Oct	2,4	8
Secale cereale	End of Vegetation	28–Oct	1,6	10



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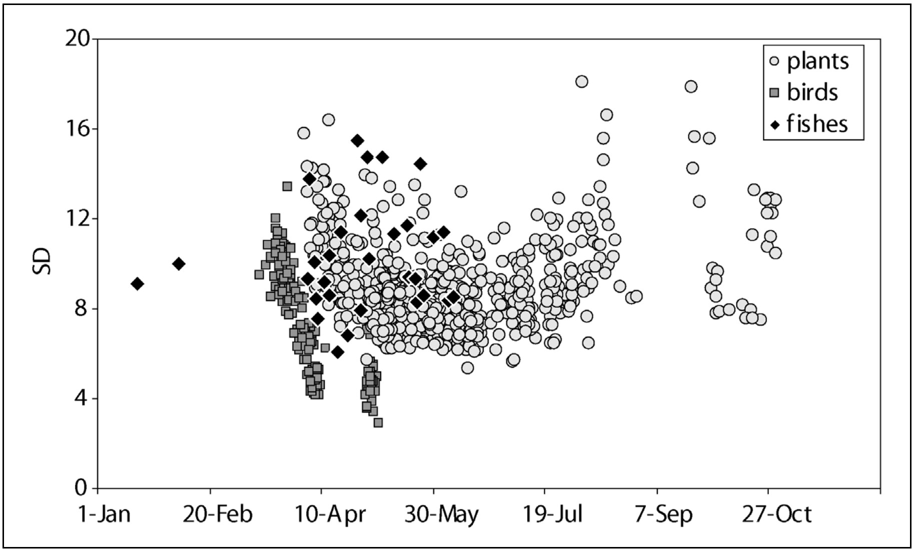

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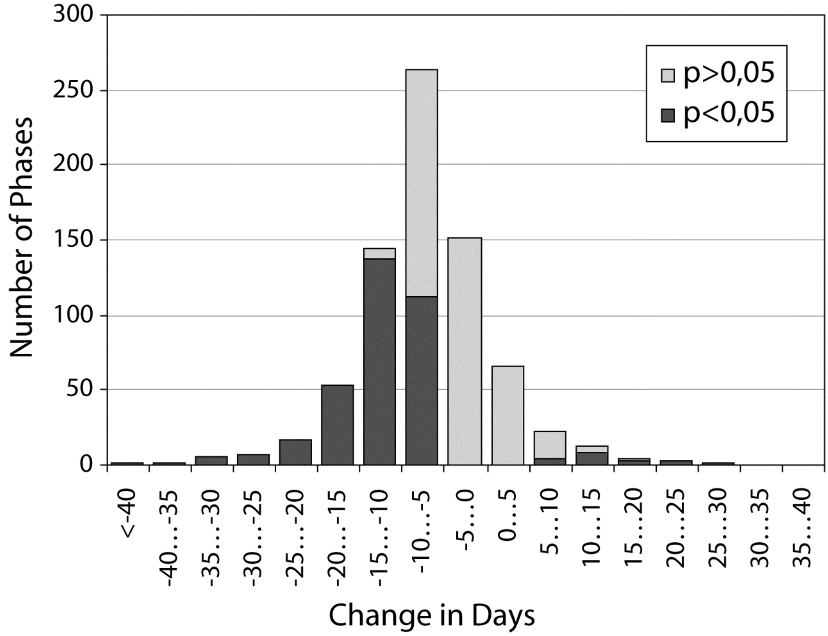

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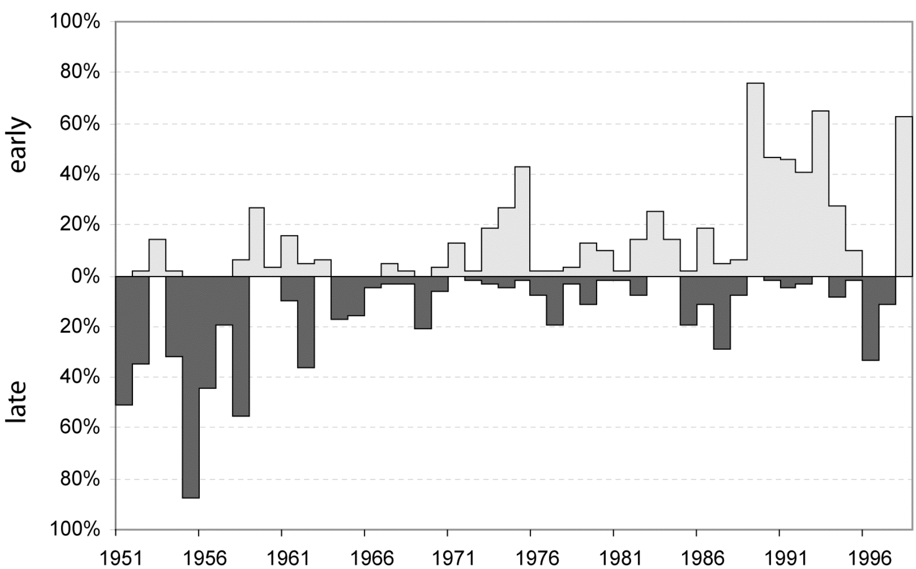

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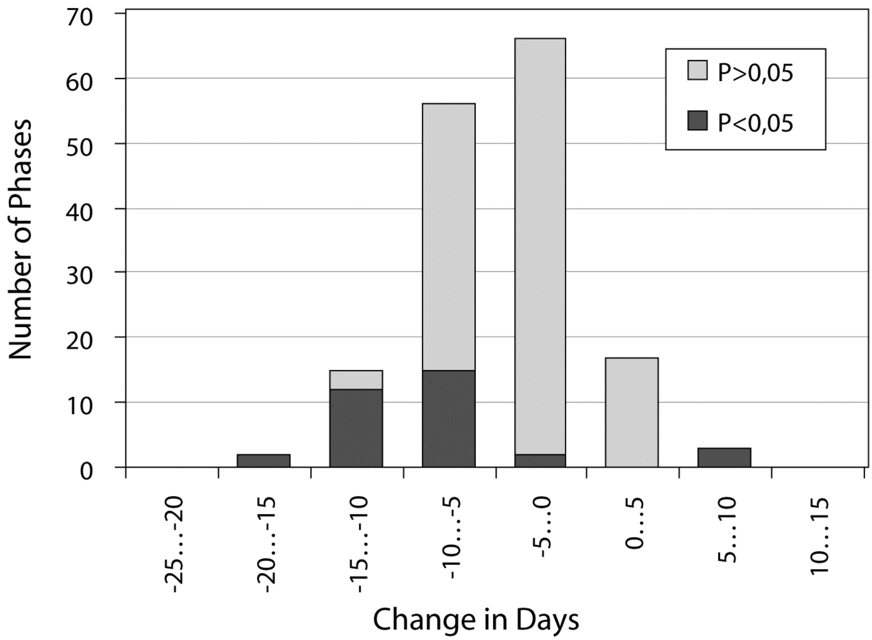

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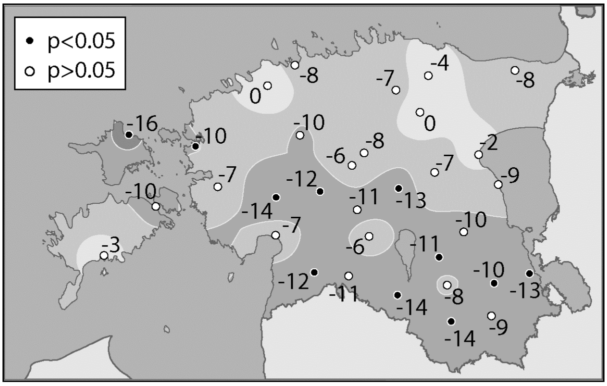

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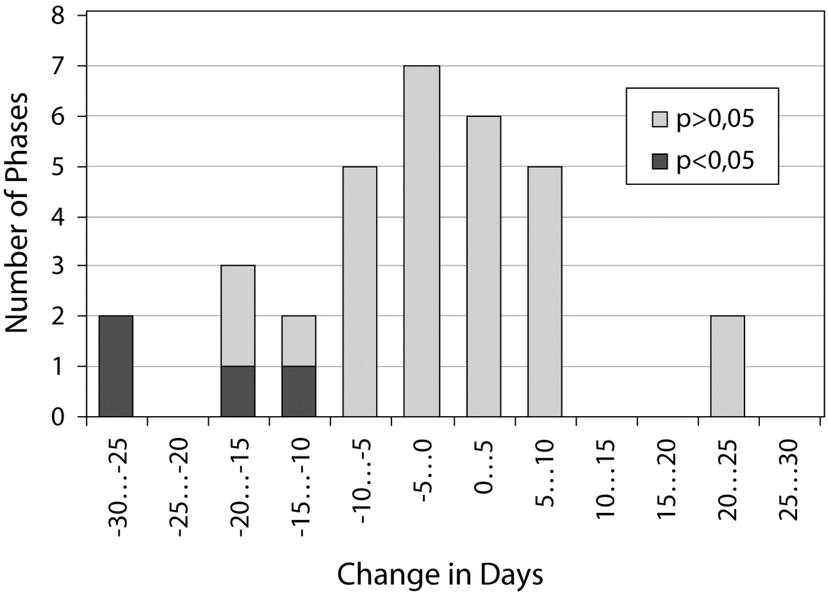

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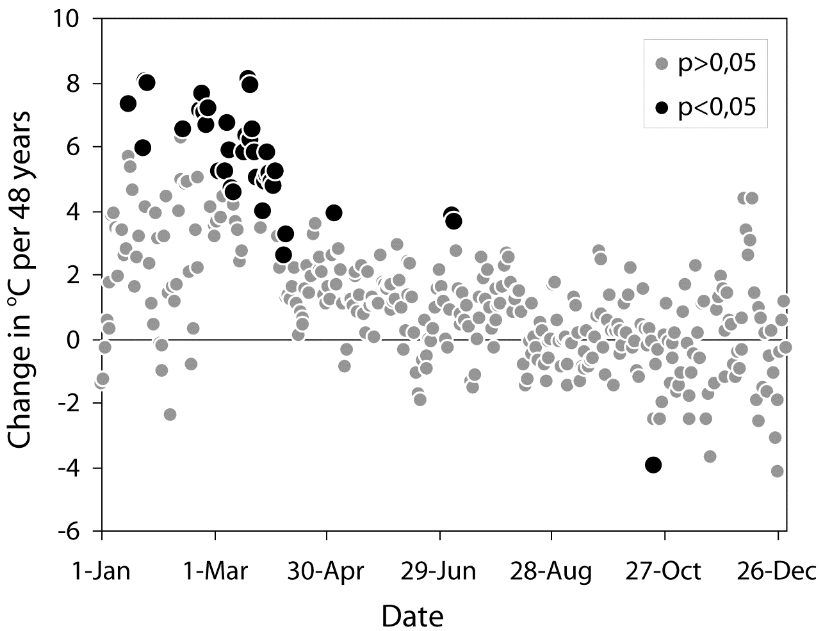

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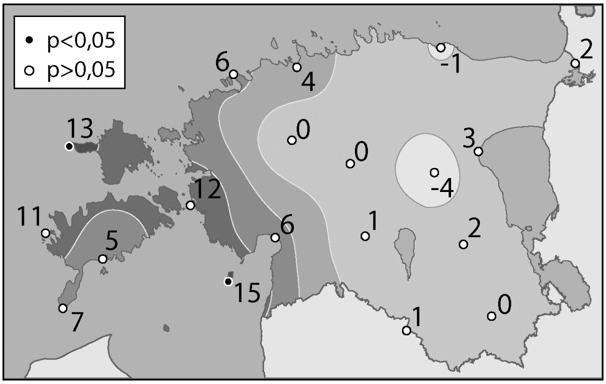

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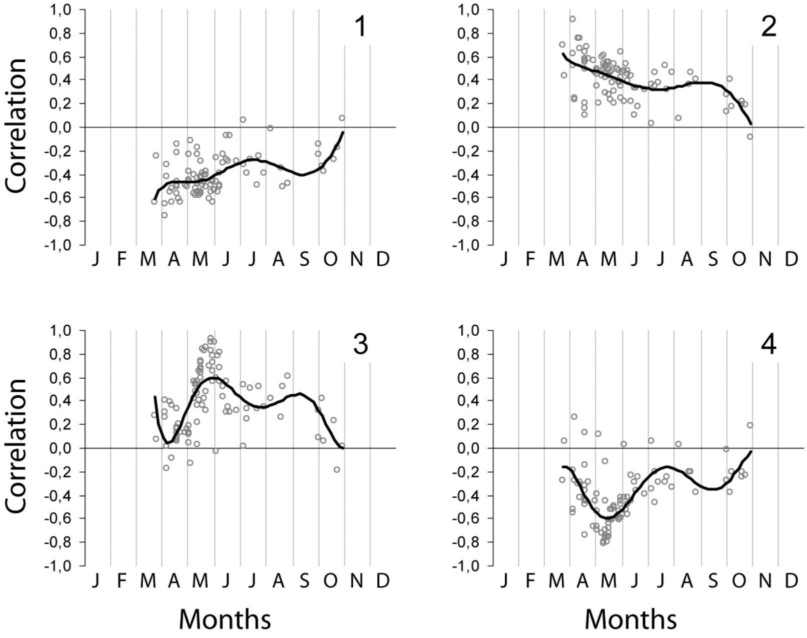

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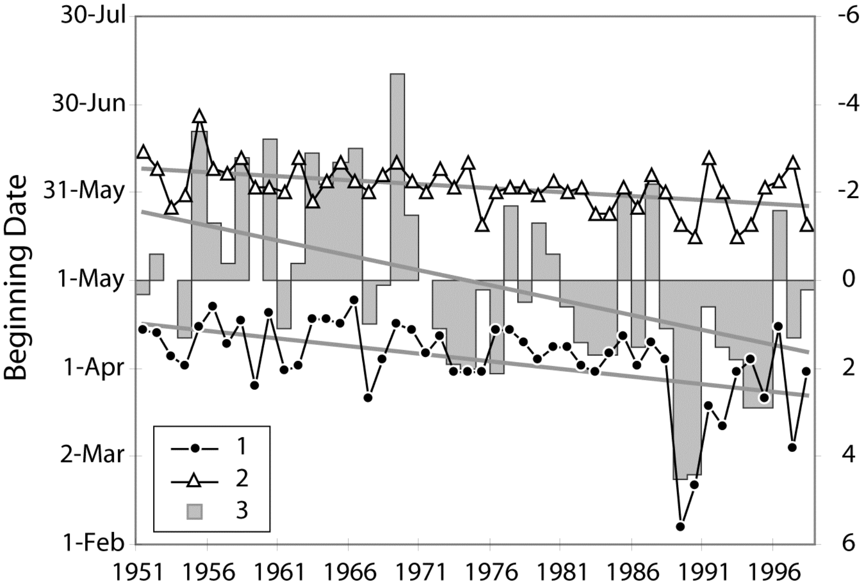

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2000–2002	University of Tartu, MSc in geography
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Professional employment

2003–	University of Tartu, Institute of Geography, Researcher
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Scientific work

2004–	EU RD program COST 725, working group III member
2000–2002	FP5RTD Phenological Observations and Satellite Data (NDVI) – Trends in the Vegetation Cycle in Europe (POSITIVE) EVK2-1999-00109, working group member

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