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Phenological maps of Europe

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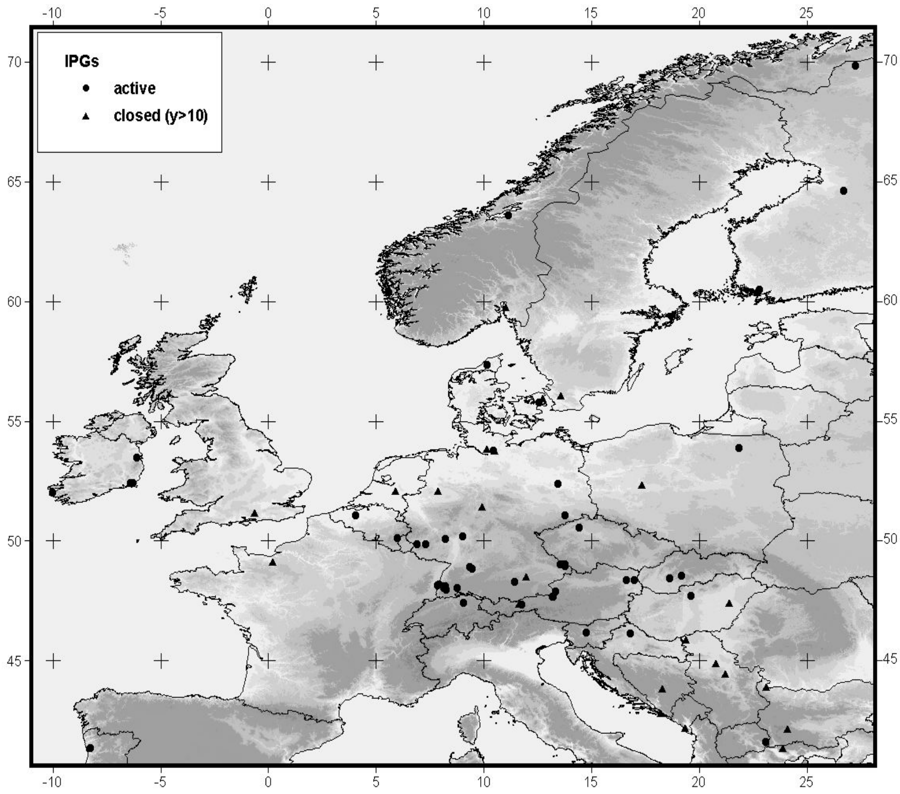

Fig.: Locations of the International Phenological Gardens (IPG) in Europe. Active and already closed stations with observations for more than 10 years are shown.

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Phenological Maps of Europe

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Abstract

The geographical distribution of the timings of phenological phases are a precondition for detecting regional trends of the annual timings of phenological phases and finding their relationships to climate changes. Therefore phenological maps of Europe were computed showing long-term means, trends and annual timings of extreme years. In this study maps of the beginning, the end and the length of the growing season as means over the years 1961 to 1998 as well as for the warm year 1990 are presented. Strong dependences on altitude, longitude and latitude were computed both for single phenological phases and the end resp. the beginning of growing season. The goodness of fit for the regression equation was between 32% for the end and 83% for the beginning of growing season. A high conformity was found with the results of similar investigations.

Key words: Phenology · Maps · Growing season · GIS · Europe

Introduction

The annual course of the seasons is reflected by the regularity of the starting dates of phenological phases of plants, like e.g. the unfolding of leaves or the beginning of leaf fall. Phenological maps show the geographical distribution of the annual timings of phenophases, thus reflecting the dynamics of seasons.

The use of phenological maps is manifold: They form the base for maps showing the climatological suitability for growing crops, the risk of frost damage of fruit trees or the climatic risks of plant diseases and pests affecting crops (Rötzer et al.1997). Calculating the water-balance of crops (Rötzer et al. 1997), investigating the relationship between climate and vegetation (Walkovszky 1998) or calibrating remotely sensed data (Schwarz 1999) are further applications of phenological maps.

Phenological maps have already been presented by Lieth and Radford (1971) showing the beginning of flowering of *Cornus florida* or by Chmielewski (1996) showing the leaf unfolding of *Betula pubescens.* Further on phenological maps are part of nearly every climatic atlas as e.g. the climatic atlas of Bavaria or Nordrhein-Westphalen. However, one of the first phenological maps of Europe was created by Schnelle (1955), who founded the International Phenological Gardens (IPGs) in 1957. After data have been collected in these International Phenological Gardens for over 40 years, now a new kind of phenological maps based on a homogenous and proofed data set can be made.

The aim of this study was the mapping of annual timings of phenological phases for long-term means and for extreme (warm or cold) years. Maps showing the beginning, the end and the length of growing season were computed as well. For all seasons the dependences of phenophases on geography were detected. The phenological maps made for Europe form the base for investigations concerning the relationships between phenology and climate variability.

Data and Methods

The phenological maps of Europe base on observations of the IPGs. In all gardens of this network up to 23 species of only vegetatively propagated trees and shrubs were planted. Ranging across 28 latitudes from Scandinavia to Macedonia and across 37 longitudes from Ireland to Finland in the North and from Portugal to Macedonia in the South the IPGs cover wide regions of Europe (see front page, Chmielewski 1996). Since the establishing of the first garden in 1959 about 60,000 phenological data have been collected in up to 66 gardens until 1998.

Before mapping phenological phases a validity check of all observation data had to be done. All observations differing from the stations' means for more than 30 days were selected. After the observers' remarks had been checked, the selected data were compared with the written records and with the same phenophases of the nearest stations resp. of the natural regions. In addition, the data were collated to the observations of the pre- and post-phenophases as well as to similar terminated phenophases of the same stations.

Gaps in the time series were filled by using linear regression-models with one independent parameter (=regressor). Regressors were either the same phenophase of the nearest station, the same phenophase of the natural region, the pre- or post-phenophase at the same station or a similar terminated phenophase at the same station. For the calculation of a missing value the best regression-model regarding the coefficient of correlation was chosen. Missing values were only calculated if the correlation coefficient was higher than 0.70.

The annual timing of phenophases is influenced mainly by air temperature. In spring the temperature across Europe decreases from south to north and from the maritime regions in West Europe to the continental regions in East Europe. With increasing altitude the average air temperature decreases 0.65 °C/100m. Thus altitude, latitude and longitude provide the possibility to map the beginning of phenological phases by using multiple regression analysis.

The relationships between the annual timing of a phenological phase and altitude, latitude and longitude could be determined using the observations of the IPGs. By means of the resulting equation the beginning of a phenological phase can be calculated for any given location of the map within the region of the network:

$$pp[x,y,z] = c + a_x*x + a_y*y + a_z*z \qquad (1)$$

where pp[x,y,z] is the starting date of the phenological phase at the altitude z, the longitude x and the latitude y, c is the constant and a_x , a_y , a_z are the regression coefficients.

Eq. 1 computes the beginning of a phenological phase depending on the regressors altitude, longitude and latitude. The residual received from the difference between the observation at the IPG and the result of Eq. 1 includes the error as well as other unknown influencing factors. These are e.g. the plant conditions or the plant age as well as the micro-climate of the location, which shows strong relationships to exposition, inclination or the surroundings.

However, as the standard errors of the regression equations range from values of 2.8 to 8.2 days (Table 1), altitude, longitude and latitude are the main influencing factors. Nevertheless the standard error has to be regarded when the classifications of the maps are made.

By using a digital elevation model with a horizontal grid spacing of 30 arc-seconds (approximately 1 km) and Eq.1, phenological maps showing means, trends and starting dates of extreme years as well as maps of the beginning, the end and the length of the growing season were computed.

For a better orientation national borders, cities and rivers can be added to the maps.

Results

In Table 1 the results of the regression analysis for different phenological phases are listed. They are assorted according to their annual timings.

Tab.1: Shift of the beginning of selected phenophases with altitude (a_z), longitude (a_x) and latitude (a_y). The results of the multiple regression analysis are derived from the means of the period 1961-1998 *(mean* average annual timing for Europe 1961-1998, *n* number of IPGs, *c* constant of the regression equation, *r²* goodness of fit, *s* standard error, *p* error probability). phases: *BE* beginning, *B* beginning of flowering, *BO* leaf unfolding, *M* mayshoot, *F* first ripe fruits, *E* end, *BF* beginning of leaf fall)

plant	**phase**	**mean**	**n**	**c**	**a_z** d/100m	**a_x** d/100km	**a_y** d/100km	**r²** %	**s**	**p**
Salix smithiana	B	85	46	-78.7	1.2	1.6	2.6	90	4.6	**
Ribes alpinum	BO	101	43	-55.1	3.5		2.6	79	7.4	**
Growing season	BE	111	37	-32.6	3.1	0.5	2.3	83	5.2	**
Betula pubescens	BO	113	47	-16.0	2.8	0.7	2.1	91	3.5	**
Prunus avium B	B	116	34	-37.8	2.9	0.7	2.5	93	3.5	**
Picea abies F	M	133	49	3.9	3.1	0.4	2.0	81	6.4	**
Pinus silvestris	M	133	38	-20.9	2.6	0.4	2.6	87	5.6	**
Robinia pseudo.	B	147	18	-55.2	4.6	0.5	3.5	97	2.8	**
Sambucus nigra	B	154	15	-6.7	3.4		2.8	84	4.5	**
Prunus avium B	F	181	17	-0.3	3.7		3.2	86	5.4	**
Sambucus nigra	F	240	12	42.8	2.9		3.6	52	7.5	+
Ribes alpinum	BF	298	21	364.4	-1.6	-0.8	-1.0	42	8.2	*
Growing season	E	303	29	310.6	-1.0	-0.2	-0.1	32	6.5	*
Salix smithiana	BF	308	25	267.4		-0.4	0.8	46	4.4	**

**: $p < 0.001$; *: $p<0.01$; +: $p < 0.05$

With the exception of the phenophase ‘first ripe fruit’ of *Sambucus nigra* all regression equations were highly significant ($p<0.01$). The goodness of fit r² was obtained for spring- and summer-phenophases with values between 79% (leaf unfolding (BO) *Ribes alpinum*) and 97% (beginning of flowering (B) *Robinia pseudoacacia*), while for late summer- and autumn-phenophases the goodness of fit was smaller like e.g. the leaf-fall of *Ribes alpinum* with 42% ($p<0.01$).

Almost all phenological phases of Table 1 show a dependence on latitude and altitude (exception: leaf fall (BF) *Salix smithiana*), whereas longitude is a significant regressor for only a couple of phenological phases: Spring-phenophases start later from west to east with 0.4 to 1.6 days per 100 km, summer-phenophases show no change and autumn-phenophases start earlier from west to east with up to 0.8 days per 100 km.

Similar values for the seasons can be found for altitude and latitude: High dependences in spring and summer, which means a later starting of the phenological phases with increasing altitude resp. latitude, and less or no dependences in autumn. Leaf-fall of *Ribes alpinum* e.g. starts 1.6 days earlier per 100 m increasing altitude and 1.0 day earlier per 100 km from south to north, whereas the leafs of the same species unfold 3.5 days later per 100 m increasing altitude and 2.6 days later per 100 km from south to north.

To map the beginning, the end and the length of growing season indicator phases have to be defined. The beginning of the growing season was represented by the average date of leaf unfolding of *Betula pubescens*, *Prunus avium*, *Sorbus aucuparia* and *Ribes alpinum.* For the end of the growing season the average dates of leaf fall of *Betula pubescens*, *Prunus avium*, *Salix smithianta* and *Ribes alpinum* were used. The difference between the end and the beginning of growing season was defined as the length of growing season. These phenophases were chosen because long time series can be provided by most International Phenological Gardens. Furthermore, the greatest part of the vegetation starts greening resp. ends in this period.

The dependences of the beginning resp. the end of the growing season on altitude, longitude and latitude – averaged over the years 1961-1998 - can be derived from the regression coefficients averaged over the indicator phases. Thus the beginning of growing season starts 3.1 days later per 100 m altitude, 0.5 later days per 100 km from west to east and 2.3 days later per 100 km from south to north (r^2= 83% with $p<0.001$). Showing a goodness of fit of 32% ($p<0.02$) the growing season ends earlier with increasing altitude (-1 days per 100 m), increasing longitude (-0.2 days per 100 km) and latitude (-0.1 days per 100 km). Consequently the length of the growing season shortens 4.1 days per 100 m increasing altitude, 0.7 days per 100 km from west to east and 2.4 days per 100 km from south to north.

Averaged over the years 1961 to 1998 growing season starts in most regions of Europe between April 10 and April 25 (Figure 1). Whereas the British Isles - with the exception of Scotland -, Belgium, the Netherlands, the northern part of France as well as Hungary, Croatia and the former Republic of Yugoslavia show a beginning of growing season between April 5 and 15, an earlier beginning before April 5 was calculated for southern France, northern Portugal and Spain and for most of the coastal regions of the Mediterranean Sea. A late beginning of the growing season between April 15 and 25 can be seen in most parts of Denmark, Germany, the Czech Republic and Poland. After April 25 growing season starts - averaged over the years - in Scandinavia and in the Baltic Sea region.

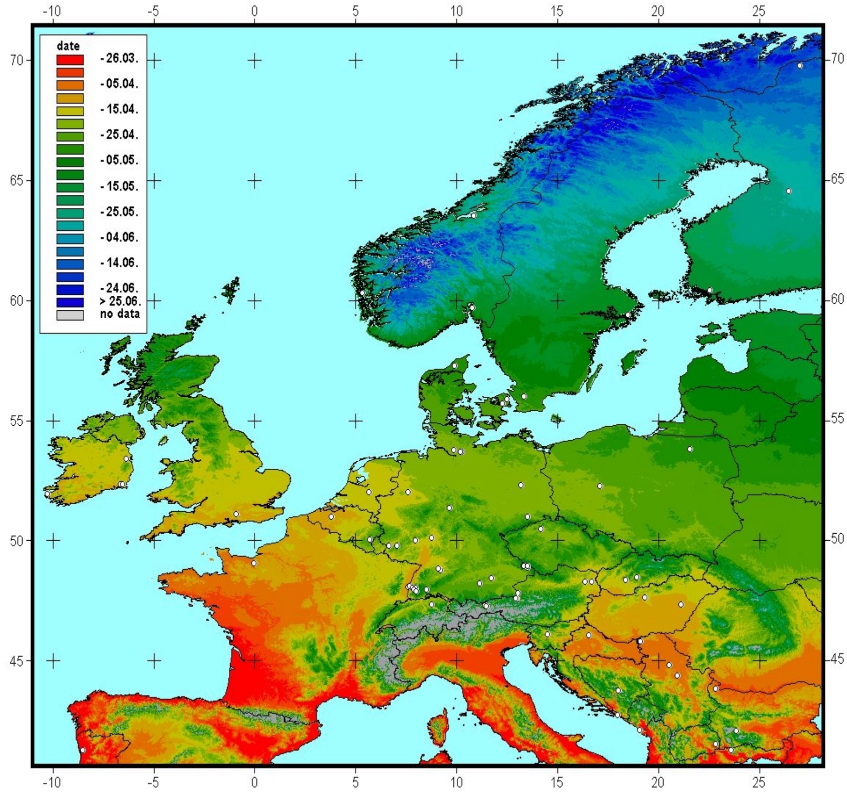

Figure 1: Average beginning of the growing season in Europe for the period 1961-1998

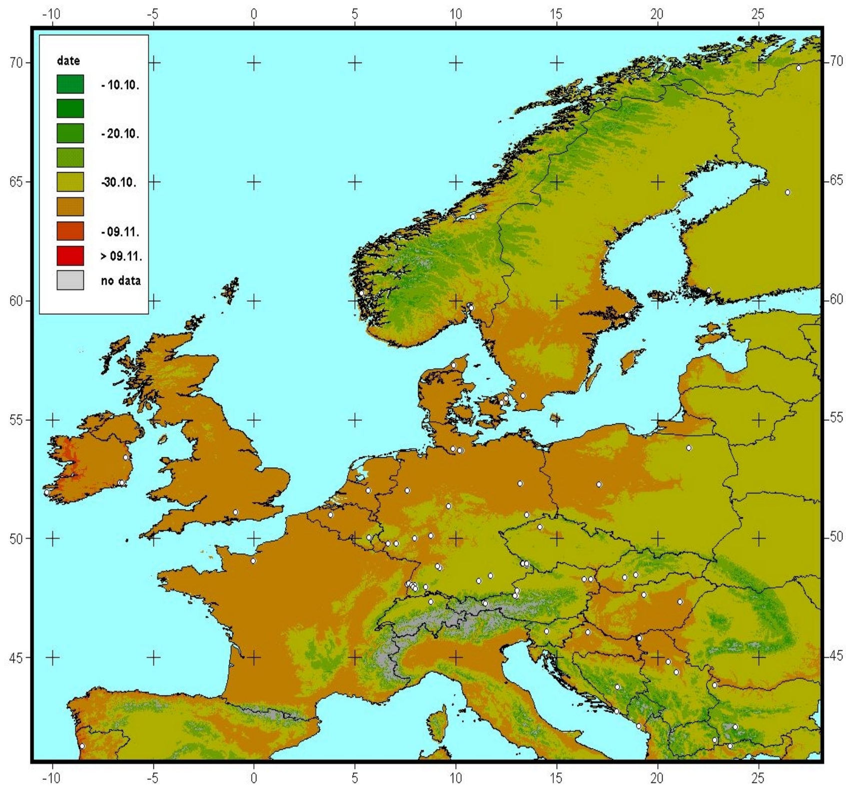

Figure 2: Average end of the growing season in Europe for the period 1961-1998

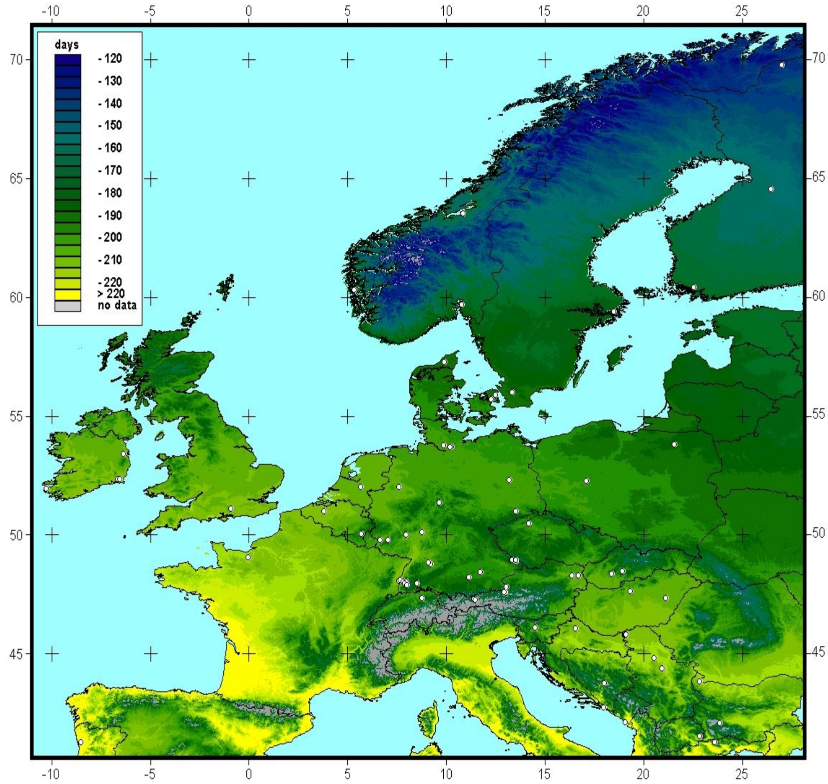

Figure 3: Average length of the growing season in Europe for the period 1961-1998

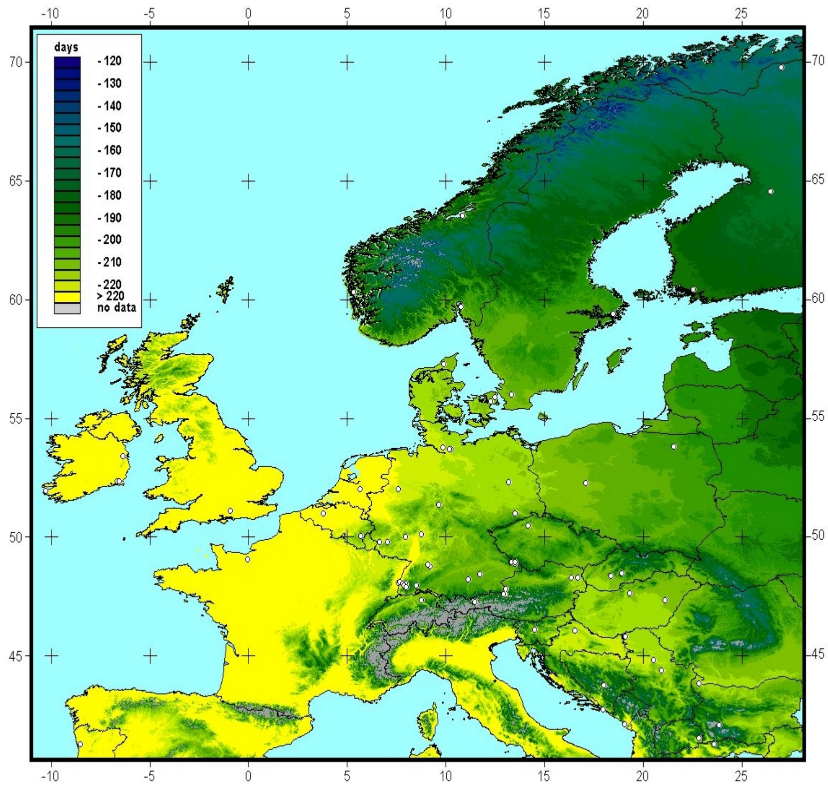

Figure 4: Length of the growing season in Europe of the year 1990

In mountainous regions like the Alps or the Dalmatian Mountains great differences of the beginning of growing season can be seen: While alpine valleys often show a beginning of growing season before April 15, in high altitudes - in about 1500 m - growing season starts nearly 4 weeks later. The latest beginning after May 30 is observed in the highlands of Norway and north of the polar circle.

The end of growing season (Figure 2) does not have the broad range of annual timings the beginning of growing season does. While in eastern Europe, in most parts of Scandinavia, in southern Germany, in Switzerland, in Austria as well as in the Czech Republic growing season ends between October 25 and 30, the western part of Europe, northern Germany, Hungary and southern Europe show slightly later dates between October 30 and November 4. In high altitudes like the Alps, the Carpathian Mountains, the Dalmatian Mountains or the Scandinavian Mountains the end of growing season can be observed already before October 25.

As the end of growing season lies in a small spectrum all over Europe the lengths of growing season mainly depend on the beginning. Longest growing seasons with over 220 days can be found in the southern part of France and in the coastal regions of southern Europe (Figure 3). In large parts of Ireland, in southern England, in the Netherlands, in Belgium, in most parts of France, in Hungary as well as in southern Europe without the mountainous regions growing season lasts between 200 and 220 days. In Scotland and Denmark, in most regions of Germany, in Switzerland, Austria, the Czech Republic, Slovenia, Poland and in the southern part of Sweden growing season lasts less than 200 days but more than 180 days. Shorter growing seasons with less than 180 days are calculated for high altitudes as well as for nearly entire Scandinavia. High altitudes in Scandinavia as well as the regions north of the polar circle show growing seasons under 150 days.

One of the warmest years in Europe in the period 1961 to 1998 was the year 1990. The length of growing season in this year can be seen in Figure 4. In most parts of the British Isles, of France and of Belgium, in the Southwest of Europe as well as in the Netherlands and in the Rhine Valley in Germany growing season lasts over 220 and up to 240 days. In the Southeast of Europe, in nearly entire Germany, in the western part of Poland, in the Czech Republic, in Austria, Switzerland, Slovakia and Hungary the length of the growing season was between 200 and 220 days in 1990, whereas eastern Europe and the northern Baltic Sea region shows lengths of 180 to 200 days. Shorter growing seasons were only found in northern Scandinavia and in high altitudes over 800 m.

Averaged over all regions of Europe the year 1990 shows a lengthening of the growing season of 12 days compared to the long-term mean, whereas for the cool year 1970 a shortening of the growing season of 10 days was found. Further maps of selected phenophases (long-term means, trends, single years) can be seen on our homepage (http://www.agrar.hu-berlin.de/pflanzenbau/agrarmet/).

Discussion

Averaged over the spring-phenophases (BO *Ribes alpinum* and *Betula pubescens*, *B Prunus avium*, M *Picea abies* and *Pinus silvestris*) leaf unfolding, mayshoot or flowering begin 3 days later per 100 m altitude, 0.6 days later per 100 km from west to east and 2.4 days later per 100 km from south to north (Table 1). The dependences of the starting dates of the summer-phenophases (B *Robinia* *pseudoacaccia* and *Sambucus nigra*, F *Prunus avium* and *Sambucus nigra*) are strong for altitude and latitude, whereas there is no significant dependence on longitude. Autumn-phenophases show only slight dependences on altitude, longitude and latitude.

All maps presented show annual timings of phenophases based on the geographical factors altitude, longitude and latitude. Other geographical factors which e.g. are described by Sachweh and Würländer (1995) could not be included in the mapping of the annual timings of phenophases because of the missing geographical data basis like e.g. the 'building density index'. The difference of the mean starting dates between rural areas and areas with high building densities was calculated by Rötzer et al. (2000) or by Sachweh and Rötzer (1997) with 2 to 4 days for spring-phenophases based on values of different national networks. For the IPG we found an earlier beginning of spring-phenophases in urban areas of 2 up to 5 days while autumn-phenophases show a later beginning with 3 to 4 days.

Exposition and inclination could not be considered when mapping the annual timings of phenophases for Europe because of the scale of the maps, though phenophases show an earlier or later beginning with up to 14 days depending on exposition and inclination (Kreeb 1954, Schnelle 1955, Chen 1994).

The influence of different varieties of a plant species amounts up to 12 days depending on site, plant species and phenophase (Table 2).

Tab. 2: Differences in the annual timings of mayshoot (M), beginning of flowering (B) and leaf-unfolding (BO) of two varieties from *Picea abies* (121 and 122), *Prunus avium* (241 and 242), *Fagus silvatica* (221 and 222), and *Quercus robur* (256 and 257) at different International Phenological Gardens

IPG-No	station	M *Picea abies*	B *Prunus avium*	BO *Fagus silvatica*	BO *Quercus robur*
2	Bergen (Norway)	5	7	5	
3	Oslo (Norway)	3	3	2	
5	Stockholm (Sweden)	3	2		
12	Aalborg (Denmark)	11	6		
14	Wexford (Ireland)	3	-3	9	
18	Gent (Belgium)	4	-2	3	0
44	Mikolajki (Poland)	3	-1		
23	Muenden (Germany)	7	3	7	-1
37	Freising (Germany)	3	1	5	3
46	Zurich (Switzerland)	12	0	9	
50	Vienna (Austria)	8		0	
52	Zvolen (Slovakia)	4	1	6	0
56	Zagreb (Croatia)	8	0	8	3
57	Sombor (Serbia)	12	-1		1
61	Beograd (Serbia)	4	0		-1
55	Ljubljana (Slovenia)	9	1	8	
65	Saloniki (Greece)	7			
58	Sarajevo (Bosnia-Her.)	6	1	0	1
45	Porto (Portugal)	-1			
	mean	**6**	**0**	**6**	**1**

On the average the varieties of *Picea abies* (mayshoot) and of *Fagus silvatica* (leaf unfolding) show differences of 6 days, while the differences of the varieties of *Prunus avium* (beginning of flowering) and *Quercus robur* (leaf unfolding) were much smaller (0 resp. 1 day).

In the phenological maps shown here the influence of variety could be excluded because the IPG-data base on observations made on genetically identical plants. All the other influences listed above are not enclosed in the phenological maps. However, as the goodness of fit r² with values of up to 97% as well as the standard deviations with values between 2.8 and 8.2 days show, altitude, longitude and latitude are the most relevant influences. Only autumn-phenophases and thus the end of the growing season have smaller goodness of fit values, which means there are influences of other unknown factors.

In addition to the regression coefficients of altitude, longitude and latitude based on the phenophases of the International Phenological Gardens 'IPG 61-98', Table 3 shows the coefficients of 'DWD 51-80' and of 'DWD 61-90' computed for Bavaria on the base of the observations made by the German Weather Service for the period 1951 to 1980 (Rötzer 1996) resp. for the period 1961 to 1990 (Rötzer et al. 1997). Despite of other periods and another data-base the results correspond with ours to a great extent.

Tab.3: Regression coefficients of the altitude (a_z), longitude (a_x) and latitude (a_y) for different phenophases (*B* beginning of flowering, *M* mayshoot, *F* first ripe fruits) on the base of observations made by the International Phenological Gardens for the period 1961-1998 (IPG 61-98), by the German Weather Service for the period 1951-1980 (DWD 51-80) and by the German Weather Service for the period 1961-1990 (DWD 61-90) (Rötzer 1996, Rötzer et al. 1997)

Plant	**phase**	**a_z** (d/100m)			**a_x** (d/100km)			**a_y** (d/100km)		
		IPG 61-98	DWD 51-80	DWD 61-90	IPG 61-98	DWD 51-80	DWD 61-90	IPG 61-98	DWD 51-80	DWD 61-90
Prunus	B	2.9	3.3		0.7	1.2		2.5	3.3	
Sambucus nigra	B	3.4	3.4	3.5	0.0	0.0	0.0	2.8	2.7	3.2
Sambucus nigra	F	2.9	3.1		0.0	0.0		3.6	1.3	
Prunus	F	3.7	3.4	4.2	0.0	0.0	-1.3	3.2	0.0	0.7
Picea abies	M	3.1		2.5		0.4		0.0	2.0	2.2
Tilia cordata	B	5.2	3.2		0.0	0.0		2.0	2.0	
mean		**3.5**	**3.3**	**3.4**	**-**	**-**	**-**	**2.7**	**1.9**	**2.0**

Nearly all regression coefficients are on the same level. With the exception of the beginning of flowering of *Tilia cordata* (a summer-phenophase) the differences between the altitude coefficients of the different data sets are smaller than 0.6 days/100m. The mean altitude coefficient of the IPG-phenophases with 3.5 d/100m corresponds well with the one of 'DWD 51-80' with 3.3 days/100m and of 'DWD 61-90' with 3.4 days/100m.

Mostly no relationship to the phenophases of the different data bases was found for the longitude coefficients.

The latitude coefficients show similar results for the different data sets. Except the phenophase first ripe fruits of *Sambucus nigra* and *Prunus* all differences are lower than 0.8 days/100m. On the average all timings of IPG-phenophases show a dependence on latitude with 2.7 d/100km. Compared to the values of 'DWD 51-80'

(1.9 days/100km) and ‘DWD 61-90’ (2.0 days/100km) there are only small differences. In addition it must be taken into account that the regression coefficients of ‘DWD 51-80’ and ‘DWD 61-90’ were calculated on the base of South-German stations only.

Schnelle (1955), König and Mayer (1988) or Chen (1994) computed a later beginning of spring-phenophases by 1 to 3 days per 100 m increasing altitude for different regions of Europe. The later beginning of first spring with 2.5 days from south to north and with 0.7 days from west to east, which Wimmenauer (1897) found for Germany, corresponds well with our results.

When comparing maps of the beginning of flowering of *Sambucus nigra* based on the data of the German Weather Service (Rötzer et al. 1997) to the same map based on IPG-data, we can see similar structures, which means similar annual timings. However, two main differences turn up: First, a shift of about 2 to 4 days from the map of the German Weather Service (period 1961-1990) to the map of the IPG appears, which is probably due to the warmer period of the IPG-data (Chmielewski and Rötzer 2000). Second, the regression equation for the map of the German Weather Service includes - besides the regressors altitude, longitude and latitude - the ‘building density index’ showing an earlier flowering in areas with high building densities, i.e. in urban areas.

The maps of flowering of *Robinia pseudoacaccia* Walkovszky (1998) presented for the periods 1951 to 1980 and 1983 to 1994 correspond well with the map of the beginning of flowering on the base of the IPG-data for the period 1961 to 1998.

Kramer (1996) found an advancing of leaf unfolding for *Fagus silvatica* with 3.6 days/°C and Beaubien and Freeland (2000) calculated the advancing of spring flowering with 4 days/°C. Taking into account that temperature decreases 0.65 °C per 100 m altitude, we found - based on the regression coefficients for the altitude - an advancing of leaf unfolding for *Fagus silvatica* of 3.2 days/°C and an advancing of the spring-phenophase beginning of flowering of *Prunus avium* of 4.5 days/°C. While Walkovszky (1998) found that *Robinia pseudoaccacia* flowers earlier with 7 days/°C, we calculated 7.1 days/°C for the same phenophase on the base of the regression coefficient for the altitude.

The phenological maps of Europe shown here are the first published raster maps, which show the annual timings of phenological phases in detail. They form the base for future maps considering further geographical factors like the building density index, the land use or exposition and inclination.

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