

Phenological mapping in a topographically complex landscape by combining field survey with an irradiation model

Chytrý, Milan & Tichý, Lubomír

Department of Systematic Botany and Geobotany, Masaryk University, Kotlářská 2, CZ-611 37 Brno, Czech Republic; Fax +420 5 41211214; E-mail chytry@sci.muni.cz; tichy@sci.muni.cz

Abstract. A phenological map has been prepared for the Podyjí/Thayatal National Park, located on the border between the Czech Republic and Austria. The area is characterized by V-shaped river valleys deeply incised into a gently undulating landscape. Five stages of phenological development were defined, based upon phenological spectra of plant communities in late April; 96 sites, more or less regularly spaced over the area, were assigned to one of these stages using field observations of these spectra. Potential direct solar irradiation was calculated from a digital elevation model for a 25 m × 25 m grid extending over the study area. A method was developed for interpolation of phenological observations by weighted regression of phenology on the irradiation model. This interpolation enables the prediction of the local stage of phenological development across the study area without leveling out phenological patterns dependent upon small-scale topographic variation. Spring phenological events appear to be more advanced in the valleys (except for steep north-facing slopes) than in the adjacent landscape. Possible climatic processes underlying this pattern are discussed with emphasis on temperature inversions in the river valleys. Cold-air-drainage inversions reported from the valleys are probably too infrequent and of too short duration to delay plant phenology. The combined effects of advanced phenology and the increased risk of spring frost injury due to these inversions in the valleys may be an explanation for local distributional patterns of flora and vegetation.

Keywords: Austria; Climate; Czech Republic; Direct solar radiation; Podyjí/Thayatal National Park; River valley; Temperature inversion; Thermal sum.

Abbreviations: LSPD = Local stage of phenological development; PDSI = Potential direct solar irradiation.

Introduction

Phenological mapping of landscapes by comparing the seasonal development of plant communities at different sites was first proposed by Ellenberg (1954). The method has become especially popular in Germany and Switzerland where several regional phenological maps were published (e.g. Ellenberg & Ellenberg 1956; Schreiber 1968, 1983; Schreiber et al. 1977; Pflume & Bruehlheide 1994). The approach was also successfully applied to Mediterranean landscapes (Böhling 1994; Bergmeier 1998). Phenological maps are particularly valuable as a

surrogate for climatic maps, which are often not available at the regional scale. Compared to climatic mapping proper, the phenological method allows for a rapid field survey, because it makes use of simple plant development observations rather than direct measurements of climatic parameters. If relatively small regions are mapped, a dense network of phenological observations can easily be achieved, as opposed to direct climatic measurements, whose density is limited by instrumental costs and available labour.

Phenological maps reflect spatial variation in the complex of climatic factors which are most intimately related to the plants and which are often hardly measurable. In a range of applications, e.g. in agriculture, this is one of the advantages of this approach. Interpretation of phenological maps in terms of climatic factors proper, however, is difficult, as the timing of phenological events results from an intricate interplay of different climatic variables, most of them highly variable in time. In seasonal climates where vegetation development is interrupted by a cold period, such as in Central Europe, spring-phenological events are generally assumed to be most closely related to temperature. In summer and autumn the number of variables that control phenology increases and moisture availability plays an important role (Anderson 1974; Taylor 1974). Spring is therefore the most suitable period for phenological mapping, and spring maps enable the most straightforward interpretation in terms of underlying climatic patterns (Ellenberg 1954).

The timing of spring phenological events in plants from temperate regions is dependent on the breaking of the winter dormancy which includes two periods: rest and quiescence (Sarvas 1974). During the rest period, buds remain dormant due to intrinsic growth-arresting physiological conditions. After plants are exposed to chilling temperatures for some time, these conditions cease, and a period of quiescence starts, during which the buds do not grow due to unfavourable environmental conditions. Bud burst and leaf unfolding occur following the accumulation of a sum of forcing temperatures. The processes involved, as well as threshold temperatures for chilling and forcing in individual species, are insufficiently known, and several models describing possible relationships between chilling and forcing have been proposed (Hänninen 1990; Kramer 1994a).

More effective chilling may diminish the forcing requirements and advance the plant's development (Murray et al. 1989; Myking 1997). However, the effects of chilling on the results of phenological mapping are probably negligible, as the mapping jointly assesses the timing of phenological events for several plant species growing together in one site. Each species is assumed to have an optimum chilling temperature somewhere between -5 and $+10$ °C, and the intensity of chilling decreases both with positive and negative departure from the optimum temperature (Hänninen 1990; Kramer 1994a). As winter temperature fluctuates, several species with different optimum chilling temperatures may grow together in the same place, and most of them meet their chilling requirements. There may be indeed some differences among the species depending on the temperature course during a particular winter, but it is unlikely that either phenological advance or delay will simultaneously prevail in most species. Therefore, the average timing of phenological events for the entire community due to chilling will be hardly affected. The hypothesis that chilling has little effect on spring-phenological mapping is also supported by the experimental evidence that lack of chilling during warm winters can be substituted by a long photoperiod (Vegis 1964; Flint 1974; Cannell & Smith 1983; Myking 1997). A modelling exercise by Kramer (1994b) suggests that the differences in the timing of leaf unfolding in several European tree species in response to changing winter temperature are attributable to differences in response to forcing rather than to chilling.

Unlike the intensity of chilling, forcing intensity is assumed to increase with rising temperatures for all species, albeit the rate of increase may be different (Hänninen 1990; Kramer 1994a). Therefore, if several species in the same habitat are advanced in their phenological development, the habitat is likely to have received more heat during (late) winter and spring than habitats in which the same plants exhibit a later development. This pattern is related to the traditional concept of thermal sum or heat sum, i.e. the accumulated temperature above a certain threshold value over a period of time (Anderson 1974; Tuhkanen 1980; Woodward 1987; Stoutjesdijk & Barkman 1992; Cenci et al. 1997). Thermal sums are widely used for predicting the timing of phenological events and, conversely, spring-phenological maps may be roughly interpreted as maps of thermal sums for the beginning of the year.

The goal of the present study is the preparation of a spring-phenological map for a small and topographically complex landscape. While the mapping exercises published so far focused mainly on larger areas, our focus is on the topography-dependent phenological variation over short distances and deviations from macroclimatic (and 'macro-phenological') patterns. This may cause a methodological problem: the number of sites from which direct observa-

tions are necessary for map preparation increases strongly with the increasing topographic (and topoclimatic) complexity of the landscape, while on the other hand, the field survey must be accomplished during a short time span in order to minimize the bias due to the ongoing phenological development. In other words, researchers involved in field survey face a trade-off between maximizing the number and spatial coverage of the phenological observations and minimizing the duration of the fieldwork. To overcome this problem, we propose a new method in which a limited number of phenological observations are spatially interpolated by weighted regression on a potential direct solar irradiation model, derived from a digital elevation model. In this paper, we (1) provide a description of the method; (2) apply the method in the case study of a topographically complex landscape; (3) discuss some hypotheses concerning the topoclimatic relationships of the detected phenological patterns and how they relate to the local distributional patterns of flora and vegetation.

Study area

The study area is the Podyjí/Thayatal National Park and some adjacent areas on both sides of the Czech-Austrian border, between $48^{\circ} 45' - 48^{\circ} 55' \text{ N}$ and $15^{\circ} 48' - 16^{\circ} 03' \text{ E}$. There is no climatic station in the area; the following climatic characteristics are based on interpolated data from macroclimatic maps (Vesecký et al. 1958; Steinhauser & Pippin 1960; Steinhauser & Nowak 1963). The low-lying eastern part of the area (minimum altitude 208 m) is warmer and drier (mean annual temperature $8 - 9$ °C, rainfall ca. 550 mm). There are ca. 300 and 170 days/yr with mean temperatures > 0 °C and > 10 °C, respectively. Periods with these temperatures begin in the middle of February and the second half of April, respectively. Toward the northwest the altitude gradually increases to a maximum of 536 m, along with a decreasing temperature and increasing rainfall (about 7.5 °C and 620 mm, respectively). In the northwest, the period with mean temperatures > 0 °C begins in late February or early March and lasts for ca. 260 - 270 days. The period with > 10 °C begins in early May and lasts for $< 140 - 150$ days. The mean duration of the snow cover is 45 - 50 days/yr.

The valleys of the rivers Dyje and Fugnitz, deeply incised into an otherwise flat or gently undulating landscape, are a remarkable feature of the national park. They are 60 - 200 m deep, 200 - 1000 m wide at the upper part of the slopes and have a V-shaped cross-section. Numerous entrenched meanders account for frequent changes in slope aspect. The topoclimate of the valleys is assumed to differ considerably from the climate of the adjacent landscape (Quitt 1984).

Methods

Thermal sum measurements

In order to relate phenological development to the thermal sum in complex terrain, the contrast in thermal sums between south- and north-facing slopes was investigated. Temperature was measured as part of a long-term topoclimatic study on a transect across an E-W elongated ridge in the central part of the study area (Tichý unpubl.). For the purpose of this study data from two sensors at 1.5 m height on the upper part of a south- and a north-facing slope, respectively, were used. In relation to the local vegetation pattern, the sensor on the south-facing slope was located in an open woodland and that on the north-facing slope in a denser forest. As the data presented here mainly refer to the period before tree leafing, temperature differences between the two sensors may be attributed to the effect of topography rather than canopy. Temperatures were automatically recorded by a digital thermometer MultiTerm 206 (VEIT Electronics Ltd.) at 5-min. intervals. Thermal sums were expressed as cumulative sums of positive differences between the temperatures recorded at 5-min. intervals and the threshold temperature of 5 °C, beginning on 1 February 1997. The threshold temperature of 5 °C was chosen in accordance with studies considering this value as close to the minimum effective forcing temperature, above which phenological development in most temperate plants takes place.

Phenological field survey

A phenological field survey was performed from 19 - 25 April 1997, during a period of cool and cloudy weather with mean daily temperatures of about 5 °C when phenological development was rather slow. A previous detailed vegetation survey of the study area was integrated into the selection of five reference sites with different local stages of phenological development (LSPD, comparable to the phenecological stages in Bergmeier 1998). These reference sites included both potentially extremely warm and extremely cold habitats, as well as intermediate situations. They were ordered according to their stages of phenological development and numbered from 1 (phenologically most advanced) to 5 (most delayed). In each of these reference sites, phenological stages of several common species of trees, shrubs and herbs were recorded using a 10-degree scale, according to Ellenberg (1954). Stages of vegetative and generative organs were recorded separately. The records were summarized in a table of ca. 60 species for the five sites. This table was used as a reference key to the identification of the LSPD in other parts of the area, by comparison of the local phenological spectra with the spectra recorded in the reference sites.

For example, if the phenological spectrum of some site was found to be most similar to reference site 4, this site was given value 4 on the ordinal 5-degree LSPD scale. The area was surveyed by car to minimize the time difference among observations in different places. 96 sites, more or less regularly distributed over the study area, were visited and the LSPD was estimated. In later stages of the fieldwork, the table was adjusted by repeated surveys of the reference sites in order to eliminate the possible effects of ongoing phenological development

Model of potential direct solar irradiation (PDSI)

As the duration of snow cover is negligible in the study area, the effect of solar radiation on phenology is not mediated by the pattern of snow melting (Hegg 1977; Kronfuss & Stern 1978). Consequently, solar radiation affects the spring phenological events mainly by controlling the thermal sum, and the PDSI of a site over a unit of time may be used as an auxiliary indirect measure of phenological development. Spatial modelling of the PDSI pattern was based on a digital elevation model with 25 m × 25 m spacing. The relative daily sum of PDSI at the equinox, considered representative of the spring irradiation pattern, was calculated as the daily sum of PDSI reaching a slope of given aspect and inclination, divided by the daily sum of PDSI reaching a plane surface. Daily sums were obtained by summation of 120 values for the following equation, solved at 15-min. intervals:

$$\frac{\sum_t p^{1/\cos z_t} * \cos \alpha_t}{\sum_t p^{1/\cos z_t} * \cos \beta_t} * 100\% \quad (1)$$

where p is the transmittance of the atmosphere (an arbitrary value of 0.8 was used in the calculations); z_t is the solar zenith angle at time t ; α_t is the angle between the local normal to the surface and the direction of incoming direct solar radiation at time t ; β_t is the angle between the local vertical and the direction of incoming direct solar radiation at time t . Time t was set at 15-min. intervals, i.e. for 120 azimuth directions of the sun. The formula is based on the assumptions that the solar energy reaching the earth's surface is highest (1) when the sun is high in the sky and the air layer it passes through is relatively thin, i.e. $z = 0^\circ$, and (2) when it is received on a surface normal to the incoming radiation, i.e. $\alpha = 0^\circ$ (Garnier & Ohmura 1968; Revfeim 1976; Hegg 1977; Kronfuss & Stern 1978; Nunez 1980; Dubayah 1994). Solar zenith angles were determined according to Krcho (1966). Local normals to the surface were computed from the digital elevation model, according to Funk (1983). The directions of incoming radiation were calculated from the solar zenith angles.

In the complex topography of the study area, the astronomically determined time of sunrise and sunset is considerably influenced by topographic features such as ridges that intercept sunshine (Lee & Baumgartner 1966). Therefore, the angle γ_t between the local vertical and the visible horizon in the azimuth direction of the sun at time t was calculated for each cell of the digital elevation model, and $\cos \alpha_t$ was set to zero if $\alpha_t > \gamma_t$. For $z_t > 90^\circ$, the values of $p^{1/\cos z}$ were also set to zero.

Combining the field data with the PDSI model

Simple interpolation of the LSPD values by fitting a response surface to the 96 observed sites would yield incorrect estimates in sites with complex topography where the thermal sum (and consequently the LSPD) may respond strongly to variation in direct solar radiation. On the other hand, PDSI alone cannot explain the variation in the LSPD, because the phenological development on slopes of the same aspect and inclination is delayed in the macroclimatically cooler part of the area. Also, effects of temperature inversions in the valleys may play a role. Hence, the interpolation method used is based on defining local relationships between the LSPD and PDSI.

Linear regression equations of LSPD on the PDSI were calculated separately for each cell of the digital elevation model. To maximize the local aspects of relationships between these two variables, the 96 observation vectors [PDSI; LSPD] were weighted by the distance to cell k , for which the regression was calculated. The vectors from closer observations were included in the regression calculation several times. The number of repetitions of remote cells in the regression decreased with the coefficient

$$w_i = (d_{min}/d_i)^2 * 100 \quad (2)$$

where d_{min} is the distance from cell k , for which the regression is calculated, to the closest cell with LSPD observation, and d_i is the distance from cell k to the i -th cell with LSPD-observation. The values of w_i were rounded to integers. Hence, the vector for the closest cell with LSPD-observation was included in the regression calculation 100 times and vectors for the other points were included 100 to 0 times, depending on their distance from cell k . The LSPD-value for each cell k was then calculated from the known PDSI at cell k using the regression equation for this cell. Possible edge effect was not considered in this study because the edges of the area were located in a gently undulating landscape with very low variation in both PDSI and LSPD.

Results

Thermal sum measurements

Mean daily temperatures on the south-facing slope were higher and the extreme values were more pronounced than on the north-facing slope. A long rather cold period in early spring with slow phenological development suddenly changed into a warm period in early May with a rapid phenological development. A comparison between thermal sums (i.e., sums of temperatures above 5 °C recorded at 5-min. intervals) on south- and north-facing slopes, shows that in March and April, the south-facing slopes were advanced by about one month (Fig. 1). After the start of the warm period this difference was reduced to ca. 10 days. Assuming that phenological events followed a roughly similar pattern, the time of the field survey – late April – was very suitable for mapping the effects of topography on phenological development. The field survey was preceded by a relatively long period with a slowly increasing thermal sum which had led to a spatial pattern of phenological differentiation. This pattern had not yet been levelled by the advent of higher temperatures at the beginning of May.

PDSI model and phenological map

The PDSI at the equinox (Fig. 2) shows considerable spatial variability in the river valleys, where both maximum and minimum values were predicted, often at relatively short distances from each other. A striking feature of the model is the existence of patches on some steep north-facing slopes above the erosion sides of the river meanders with no incoming direct solar radiation. This indicates that there are places in the valley where the only source of solar energy in spring, autumn, and winter is diffuse and reflected radiation.

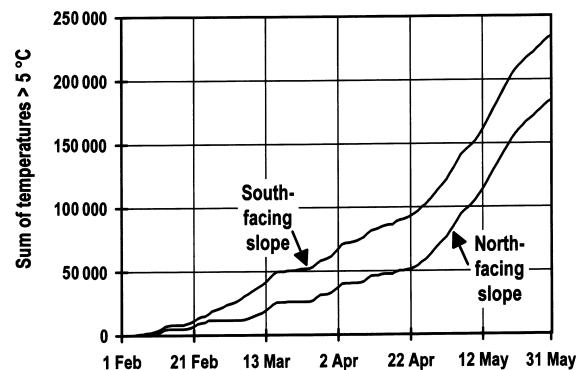


Fig. 1. Spring thermal sums on south- and north-facing slope, calculated as summation of temperatures over 5 °C recorded in 5-min. intervals.

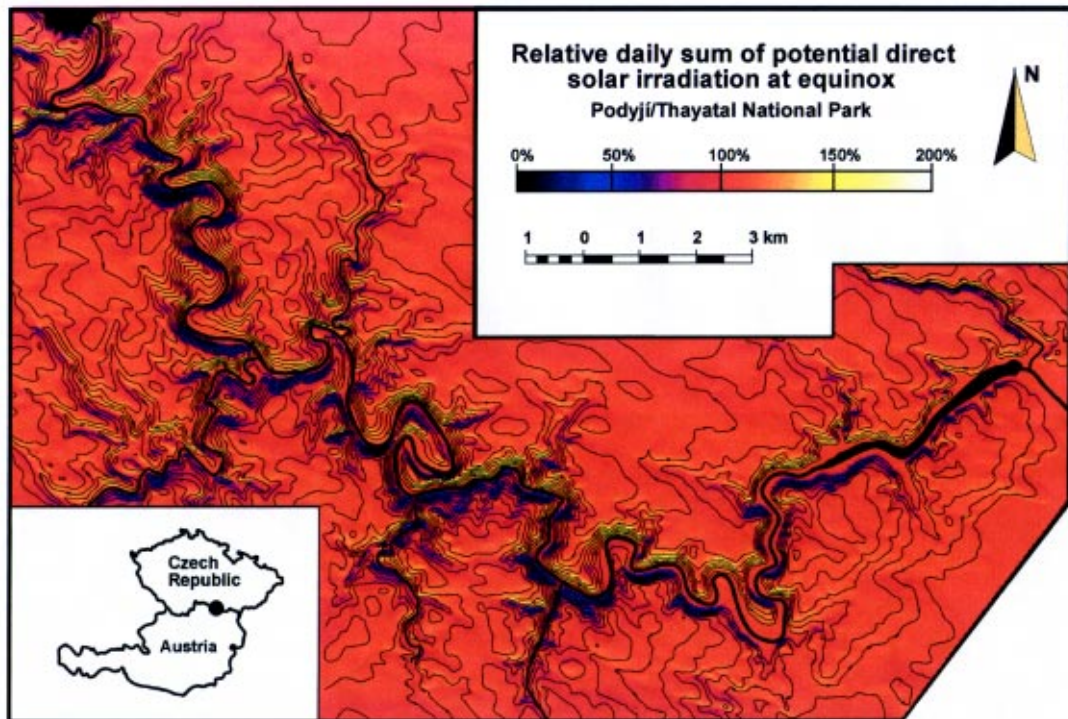


Fig. 2. Relative daily sum of potential direct solar irradiation (PDSI) at the equinox in the Podyjí/Thayatal National Park. Units are percentages of PDSI that would reach a level surface.

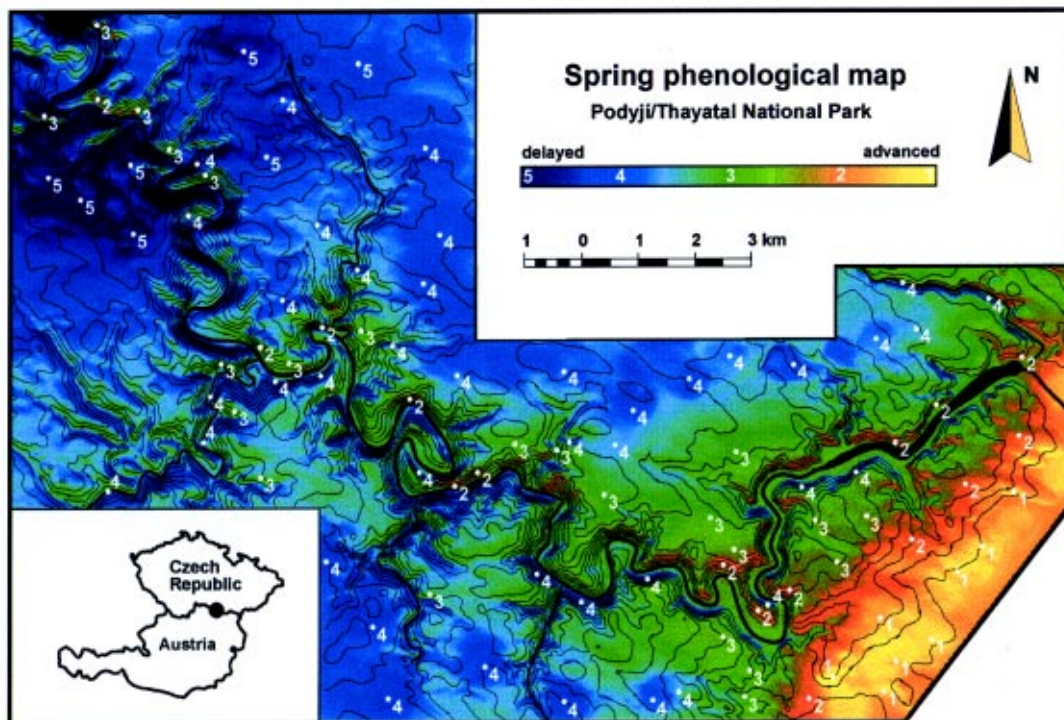


Fig. 3. Spring-phenological map of the Podyjí/Thayatal National Park. Local stage of phenological development was estimated on a 5-degree ordinal scale, with value 1 denoting the most advanced and 5 the most delayed stage. The values estimated directly in the field are indicated by the numbers 1 to 5 distributed over the area. The interpolation of these values by combining phenology with the irradiation model is expressed by a colour scale, on which the areas with the earliest advent of spring phenological events are yellow, and the most delayed areas are blue.

An analogous model for the summer solstice (Tichý, unpubl.) has shown that in summer these sites do receive a limited amount of direct solar radiation, however, the daily duration of sunshine is very restricted.

The phenological pattern in the study area (Fig. 3) is mainly dependent on macroclimate and adiabatic lapse rate. Phenological development is delayed in the cooler, high-altitudinal northwest and becomes progressively more advanced toward the warmer, low-altitudinal southeast. The difference between the northwestern and southeastern part of the area is 4 degrees on the ordinal phenological scale, but less than 3 degrees on the north-south cross-section of the river valley.

Generally, the south-facing slopes of the valleys are phenologically advanced and the north-facing slopes are either delayed or synchronized in comparison with the adjacent landscape. In the warmer southeast, the bottom of the valley shows about the same LSPD as the adjacent landscape, and in the cooler northwest the bottom is advanced.

Discussion

On the method

The presented modification of Ellenberg's (1954) method of phenological mapping allows for reducing fieldwork to several sites and producing maps by spatial interpolation. In topographically complex landscapes, incorporating the PDSI-model seems to yield a reasonable interpolation. The PDSI-model is easy to calculate from a digital elevation model. However, it is important to note that the reliability of interpolation decreases with the distance from points with known LSPD-values due to increasing standard errors of regression slopes. Also, due to weighting (Eq. 2), points with direct LSPD-observations will tend to be surrounded by identical values in their immediate vicinity in spite of possible topographical variation. That is why any patterns which are not evident in the field data and emerge merely from interpolation should be interpreted with caution and tested in the field, even if they make some ecological sense. Therefore, the actual values of the LSPD recorded in the field are plotted on the phenological map (Fig. 3) in order to indicate the sites with reliable LSPD-estimates.

Interpolated phenological maps may be used for further GIS-modelling. The phenological map presented in the current paper was used for predictive modelling of the study area's vegetation pattern (Tichý in prep.) and it was shown that a model with phenology as one of the predictors explains spatial variation of vegetation types by 11.1 % better than a model in which altitude and PDSI are used as surrogates for climatic variables.

Phenological pattern and underlying climatic processes

The phenological map has shown that in spring the V-shaped river valleys are in general phenologically advanced as compared to the flat or gently undulating adjacent landscape. Considering the relationships between the accumulation of forcing temperatures and the timing of spring phenological events, this result suggests that in spring the valleys are possibly warmer. Such an interpretation seems to be in contrast with some botanical evidence (montane species in the valleys), as well as with the fact that temperature inversions due to the formation of cold air lakes, 50 - 70 m deep, were observed in the valleys (Quitt 1984; Tichý unpubl.).

Several isolated occurrences of montane plants which are absent in the larger area were recorded in the valleys, e.g. *Aconitum variegatum*, *Dentaria enneaphyllos*, *Festuca altissima*, *Lunaria rediviva* and *Thalictrum aquilegifolium* (Grulich & Chytrý 1993; Grulich 1997). A detailed comparison of their distribution with the PDSI-map (Fig. 2) suggests that these plants are mainly concentrated in sites with very low duration of sunshine due to shading by adjacent slopes. Similarly, a montane association of ravine forest, the *Lunario-Aceretum*, is recorded only twice in a larger area, and both the occurrences are confined to such sites (Chytrý & Vicherek 1995). Insolation losses due to topographic shading cause the development of temperature inversions which peak about noon or in the early afternoon (Quitt unpubl. report). As these inversions dissipate at night, the occurrence of frosts in spring or autumn is not much more frequent than in nearby sites with higher amounts of incident radiation. Lower daily temperatures, however, imply lower sums of effective temperatures, delayed advent of spring and a shorter growing season, all of which possibly support the occurrence of montane plants and montane vegetation types. Accordingly, phenological delay was observed in topographically shaded parts of the valley (Fig. 3).

Besides inversions due to topographic shading, inversions due to cold air drainage (= micro-advectional inversions) were observed in the area (Quitt 1984). These inversions develop on clear, calm nights, when the valley slopes lose heat through long-wave radiation and cool the adjacent air which slides downslope into the valley (Geiger 1965; Yoshino 1975). However, there is no phenological evidence of cold-air-drainage inversions, not even in the valley bottoms where the highest inversion rates would be expected. This is supported by botanical evidence: in some parts of the valley bottom beyond the topographically shaded area, thermophilous species such as *Dianthus carthusianorum*, *Festuca rupicola*, *Peucedanum oreoselinum* and *Prunella grandiflora* occur in alluvial meadows, whereas they are rare or absent from the adjacent landscape above the valleys (Grulich 1997).

This phenomenon can possibly be explained by the infrequent occurrence and duration of cold-air drainage inversions in the river valleys. This may be caused by several factors. First, the drainage area of cold air is relatively small in V-shaped valleys surrounded by a flat or gently undulating landscape; in fact, it does not include much more than the valley proper (Geiger 1965). Second, almost the entire area of the valleys is forested; a complex structure of forest canopy may slow or reduce the downslope slipping of cold air. Third, night-time losses of heat from the lower parts of the V-shaped valley by long-wave radiation are possibly reduced by reflection from the valley slopes. On the contrary, radiational cooling at night is expected to be more intense in the adjacent landscape where the land surface emits long-wave radiation into the sky and cools the air above it by conduction (Geiger 1965). This is probably the reason why the map in Fig. 3 shows phenological delay in the gently undulating landscape in the northwest of the study area in comparison with the bottom of the valley.

An alternative explanation for the lack of phenological evidence of cold-air-drainage inversions is their poor detectability with the phenological method. These inversions are most intense before sunrise and dissipate in the morning. Their influence on spring thermal sums is therefore possibly negligible, because the night-time temperatures in early spring are likely to sink below the effective forcing thresholds in any case, even in the warm slope belt. With low influence on the thermal sums, cold-air-drainage inversions would hardly delay phenological events in plants.

Phenology and spatial patterns of flora and vegetation

Although cold-air-drainage inversions possibly have a negligible effect on the timing of phenological events, they may cause frost injury to sensitive plant species on the valley bottom. The combined risk of frost injury and earlier budburst in the river valleys suggest possible explanations for local phytogeographical patterns. An analysis of plant phytogeographical affinities in the study area (Grulich unpubl. data) has shown that among thermophilous plants in the valleys, species with continental distribution prevail over those with Submediterranean distribution, albeit the latter are more common in the adjacent area. The risk of frost injury may be the factor eliminating sensitive Submediterranean plants, despite the favourable prolongation of the growing season. Also, species with a southeast European (Balkan) distribution are confined to the river valleys in the study area. The presumed longer growing season and the late-spring frost events in the valleys suggest the macroclimate of the inland Balkans (Horvat et al. 1974), and according to the relative habitat constancy law (Walter & Walter 1953,

see also Chytrý 1995), the southeast European plants preferably grow in the valleys.

We hypothesize that the interaction of advanced phenology and spring frosts may also control the distribution of beech forest (*Fagus sylvatica*) which is limited to the plateaus and the steep north-facing valley slopes in the NW part of the study area and is not present in other parts of the valleys (Chytrý & Vicherek 1995). The terraces on the valley bottom, as well as gentle slopes of both northern and southern aspect are occupied by oak-hornbeam forest (*Quercus petraea*, *Carpinus betulus*), although the soils and moisture availability in summer could support the competitively superior beech as well. If the beech, as a species sensitive to damage by late-spring frosts (Ellenberg 1996), grew in these habitats, leaf unfolding would possibly be advanced by a few days, as predicted by current phenological observations. The risk of frost injury would increase, as the last episodic frosts often occur just before mid-May in the study area, particularly in the valleys where the night-time temperature drop may be enhanced by cold-air-drainage inversions. The slower rate of phenological development on plateaus and topographically shaded north-facing slopes delays leaf unfolding until the probability of frost occurrence is low. In 1997, leaf unfolding of mature beech trees in the study area was observed around 13 May, which corresponds to the predictions by Lausi & Pignatti (1973) for the given latitude and altitude. Last frost events in the study area are often recorded around this date.

Acknowledgements. We thank Vít Grulich, Pavel Prošek, Evžen Quitt, and Jaroslav Rožnovský for valuable discussions; Hagen S. Fischer, Zdenka Neuhäuslová, Eddy van der Maarel, and a referee for constructive criticism of an earlier version; Madla Chytrá and Lenka Reiterová for their help during fieldwork; Sierra D. Stoneberg for improving our English. This study was supported by the grant GA ČR 206/96/0131.

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Received 7 January 1998;

Revision received 31 August 1998;

Accepted 2 November 1998.