Statewide investigations of observed and expected changes in the phenology of wild and crop plants in Hesse and their implications for forestry and agriculture

Prof. Dr. Winfried Schröder, Simon Schönrock, Dr. Gunther Schmidt

Abstract

Background. One of the main characteristics of climate change is the rise of air temperatures. According to the Intergovernmental Panel of Climate Change (IPCC), the global mean air temperature increased by 0.74 °C between 1906 and 2005. In the federal state of Hesse in central Germany, the long-term mean air temperature of the period 1991-2009 was 0.9 °C higher compared to the climate reference period 1961-1990. The same holds true for entire Germany. With regard to different climate projections and emission scenarios, a further rise of the mean air temperatures in Hesse of up to 3 °C till the end of the 21st century has to be expected. The projected warming has a significant impact on the beginning of the phenological stages of plants over the year. Plant phenology examines different annually and periodically reappearing events in growth and development of plants. The beginning of phenological phases, such as blooming or foliation, is closely related to air temperatures. Since warm temperatures advance the course of phenological events, phenological data reflect biological response to climate change. Hence, phenological data can be used for climate biomonitoring.

Goals. The main goal of the project "Climate Change and Plant Phenology in Hesse" (HeKlimPh) was to analyse and to project the state-wide and regionally differentiated impact of climate change on the phenology of wild growing and crop plants. To achieve this goal the analysis was conducted by processing the following steps: (0) Selection and statistical description of appropriate phenological phases; (1) bivariate statistical analysis on the association between phenological onset and air temperatures; (2) GIS-based mapping of the past phenological development; (3) regional differentiated analysis of the phenological development; (4) multivariate statistical analysis on the effect of additional environmental drivers for phenological development; (5) projection of the future phenological development.

Material and Methods. For analysing and mapping the past phenological development, observations on plant phenology as well as air temperature measurements collected by the German Weather Survey (Deutscher Wetterdienst, DWD) from 1961 to 2009 were used. The German phenological monitoring network comprises almost 6,500 sites (553 in Hesse) observing more than 270 different phenological phases of wild growing plants and crop plants. The phenological observations are conducted by volunteers in accordance with standardized guidelines of the DWD. For the analysis of phenological shift, 35 phases were selected and analysed in course of the HeKlimPh project, comprising indicator phases for different phenological seasons and respective alternative phases. Additional phases described development of fruits and vine plants representing high economic importance for fruit growers. For georeferencing the phenological observation sites, coordinates were provided by the DWD enabling the creation of according GIS vector data (point layer). GIS data on several climate elements were provided as grid data sets with a spatial resolution of 1 x 1 km². For the projection of the future phenological develop-

ment (climate periods 2031-2060, 2071-2100), data of four different statistical and dynamic regional climate models (REMO/UBA, ECHAM5/COSMO-CLM, HADCM3/COSMO-CLM, WETTREG 2010) were processed. In addition, elevation data as well as soil data were used for the multivariate-statistical analyses.

Following quality and plausibility checks, the phenological observations were analysed by descriptive statistics to detect trends in the past phenological development. Subsequently, the statistical associations between air temperatures and phenological onset were calculated for each of the 35 phenological phases for the periods 1961-1990, 1971-2000 and 1991-2009 by bivariate linear regression analysis. To enhance the reliability of results, the computations were performed for whole Germany. To accomplish this task, phenological point data and temperature grids were intersected in a GIS to derive an air temperature value for each phenological observation. The regression analysis based on annual and monthly long-term mean air temperature as well as on average temperatures of those months showing the strongest correlation between air temperature and the respective phenological onset. For those phases showing a significant and at least medium correlation ($0.5 \geq r \geq 0.69$), phenological maps for each period (past and future) were calculated in a GIS by Regression Kriging. The regression equation derived for each phase and period was thereby applied to the long-term mean temperature grids of each according period to get a surface map on the onset of the respective phenological phase. Future phenological development was calculated by applying the regression equations derived for the reference period 1971-2000 by use of air temperature maps for each of the four climate models. Additionally, past and future phenological development was spatially differentiated by intersection with a map on the natural land units of Hesse. The vine-phases were analysed only for single observation sites, since the small number of observations sites did not allow for state-wide analyses.

Those phases showing low correlations ($0.2 \geq r \geq 0.49$) with air temperatures were analysed by two different multivariate statistical approaches: 1) CART-Analysis (Classification and Regression Trees); 2) multiple linear regression analysis. In addition to temperature data, several other environmental drivers were considered (e.g. precipitation, orography, soil conditions) to statistically quantify their influence on the onset of phenological phases. CART analyses the statistical association between a target variable (here: phenological onset) and several predictors as mentioned above. CART divides the input data stepwise by binary splits into two child-nodes until a given homogeneity is met. The resulting dendrograms can be used to detect those predictors that determine rather early or rather late onsets. The multiple linear regression analysis considers the correlation between one dependent variable (phenological onset) and several independent variables like those mentioned above. Thereby, only those predictors showing a significant high partial correlation with the dependent variable are integrated to the regression model. Eventually, the resulting regression equation can be used for estimating the depended variable.

Results. Almost all examined phases (31 of 35 phases) showed a shift in phenological onset to the beginning of the year between the periods 1961-1990 and 1991-2009. In average of all 35 phases, shifts in Hesse were even stronger (about 8 days) than in Germany (about 6 days). Many phases even showed a shift of more than 10 days. The strongest shifts were detected for phases in spring and early summer. In the further course of the year, some phases – especially in late summer and autumn – showed weaker shifts. At the end of the phenological year in late autumn and winter, some phases even showed a reverse shift towards the end of the year. As a result, there was a prolongation of the vegetation period, which amounted up to 10 days in some natural land units in Hesse. Some land units even showed prolongations of almost three weeks.

The bivariate statistical analysis revealed statistical associations of at least medium strength ($0.5 \geq r \geq 0.69$) for more than 70 % of the analysed phases in each of the three considered periods in the past. More than 50 % even showed a high correlation ($0.7 \geq r \geq 0.89$) between air temperatures and phenological onset. The result of the analysis corresponds with the findings for the past phenological development described above: Almost all phases for which earlier beginnings were figured out showed high negative correlation coefficients. These findings corroborate, spatially differentiated, the hypothesis that air temperature is a significant driver for phenological development. However, phases with less intense shifts in the further course of the year showed only weak correlation coefficients, especially in autumn. Eventually, for two of those phases showing shifts towards the end of the year (colouring of leaves and leaf fall of the penduculate oak) positive weak correlation coefficients were calculated. This implies that high temperatures in autumn have reverse effects on these phases: Whereas high temperatures stimulate the beginning of spring and summer phases, they retard the onset of late autumn and winter phases.

Based on the results of the regression analysis, Regression Kriging was applied to 23 of the 35 investigated phases. For instance, hazel bloom *(Corylus avellana)* in Hesse began 12 days earlier in the period 1991-2009 compared to the period 1961-1990. As could be expected, topographical patterns were reflected in the phenological maps: Lower regions indicating rather warm temperatures are characterized by early hazel bloom. In comparison, mountainous regions show late phase beginnings. These observations coincide with the regionally differentiated analysis based on the respective natural land units: For instance, in the *Northern Upper Rhine Valley* hazel bloom in average occurred more than three weeks earlier (February 10th) than in the *Eastern Hessian Highlands* (March 5th). In summary, most mountainous regions in Hesse were affected by stronger shifts of hazel bloom (not the absolute values, but the differences between phase onset of the periods 1961-1990 and 1991-2009) whereas the river valleys in the south of Hesse were affected more moderate.

Depending on the applied climate model, the long-term mean shifts of hazel bloom in Hesse range between 25 and 34 days comparing the periods 1971-2000 and 2071-2100. Regarding the shifts of the respective phase onsets for all 23 phases projected by the four climate models between the respective long-term means of the period 1961-1990 and the future period 2071-2100, the observed tendency of the past phenological development will obviously continue until the end of the 21st century. With only few exceptions, for all four models shifts of the assessed phases between the periods 2071-2100 and 1961-1990 were at least twice as high as they were between 1991-2009 and 1961-1990. For many phases, they were even three times higher or more.

For the examined vine phases, similar results were detected for three considered observation sites in the south of Hesse. Thus, depending on location and climate model, vine flowering might occur between two and three weeks earlier comparing the long-term mean onset of the periods 1971-2000 and 2071-2100, whereas vintage is expected to take place between 19 and 41 days earlier.

With regard to the calculated R^2-values, models with more statistical power were determined by applying multivariate statistical analyses compared to the results of the bivariate statistical analysis. The results of the CART-Analysis revealed, that, besides air temperature and related variables (e.g. global radiation, orography), soil condition seem to influence plant phenological events in a certain way. Referring to air temperature, especially minimum temperatures seem to force certain onsets for autumn phases. The results of the multiple linear regression analysis showed distinct correlations between air temperature and air temperature related variables only, no significant correlations to soil parameters were detected.

Discussion. For analysing the regional differences of the plant phenological development of the different natural land units in Hesse, the use of the estimated phenological surface maps was essential, especially for those natural land units with small spatial extents. Regarding only phenological data of observation sites might lead to invalid results, as some natural land units contain just few observation sites which are not representative for the whole land unit.

Referring to the bivariate statistical analysis, the applied approach of using air temperature data of only those months that showed strong correlation between air temperature and phase onset instead of using annual mean air temperature data led to more powerful regression models indicated by higher correlation coefficients. Furthermore, several statistical values (e.g. root mean square error, RMSE) were calculated to describe the quality of the surface maps. Considering all calculated maps, RMSE ranged only between 0.08 and 1.5 days.

The four climate models used for projecting the future phase onsets showed different characteristics. As two of them projected rather moderate shifts until the end of the 21st century (ECHAM5/CLM, REMO/UBA), the two others (HADCM3/CLM, WETTREG 2010) projected stronger shifts.

The multivariate statistical analyses suffered from a lack of predictors since not all environmental drivers that potentially influence the onset of phenological phases were available. Moreover, soil data with an appropriate spatial resolution were only available for Hesse, but not for whole Germany. Admittedly, application of the multivariate statistical analyses on a national scale was necessary, as the amount of observation sites in Hesse was not high enough to achieve statistical valid results. An important recommendation for the phenological monitoring is the acquisition of standardized metadata within the network, as it would promote the interpretation of phenological data.

Outlook. The observed shift in phenological development was particularly determined by climate change. Since temperature increase is expected to continue until the end of the 21st century, distinct effects on flora distribution like species migration and disappearance are very likely. By help of the phenological maps created in the course of the HeKlimPh project, appropriate adaption strategies may be implemented. In terms of agricultural management, the selection of crops and cultivars must be adjusted to the changed climatic conditions. Furthermore, farmers have to envisage increased problems related to pest control aggravated by progressing temperature increase. Another threat is the increasing risk of frost damages due to the earlier occurrence of phenological events. Referring to resources management, irrigation during summer will be necessary for larger areas and longer periods as precipitation is expected to decrease in Hesse during the vegetation period. On the other hand, there are also positive effects of climate change: the prolongation of the growing season might lead to higher yields, and cultivation of new fruit varieties might not only necessary but possible.