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Application of phenological observations in agrometeorological models and climate change research

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Abstract—This paper intends to give a brief overview on the different approaches existing in plant phenological studies. The history of plant phenological observations in Europe and Hungary shows that the aim of the observations turned from the pure scientific interest to the application in agricultural practice, and recently, to climatic studies. Modeling of phenological development is demonstrated via examples for wheat and maize. The analysis of historical data has got new horizons by the international efforts done by COST Actions. New perspectives in observations of vegetation are remote sensing data. Vegetation indices like normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) are also used for tracking the seasonal development of plants, and they give opportunity to analyze the year by year change.

Key-words: phenology, observational network, climate change, NDVI, EVI.

1. Introduction

Vegetation dynamics like growth, reproduction, and winter rest, competition for nutrients, water, and light are strongly influenced and determined by climate variables. Even in case of unchanged climate we can find big differences year by year in the start of life period simply as a result of different weather situation. A change in climate will result in a change of these dynamics. Phenology is the study of the timing of recurrent biological processes such as budburst, flowering, flight activity of insect, bird nesting, fruit ripening, and leaf fall. That is the scientific discipline, which is able to link vegetation dynamics with climate variables. The identified and recorded events are the so-called pheno-phases.

Phenological observations have long history, but the aim of observations has changed from scientific interest to practical applications, from local to global characterization of climate and biosphere interactions. The methodology of the observation could be different according to the relevant aims. It is important to know the time of the phenological phases for organizing agricultural works as well as the plant protection. Time by time organizing observational networks on national and international levels has got remarkable attentiveness, nevertheless, long-term data series are rather rare. Computerized crop simulation models contain phenological submodels since the potential biomass production is affected by the actual phenological phases. Examples of phenological models are presented for maize and wheat phenological development. Recently, in climate change studies phenology became interesting again, and great efforts have been done to collect old data series from large geographical area. The new possibilities for monitoring the vegetation on large spatial and temporal scale are remote sensing. Using vegetation indices like normalized difference vegetation index (NDVI) or enhanced vegetation index (EVI) makes possible to track phenological development of the vegetation on the scale of "landscape phenology" which differs from the traditional morphological characterization of individual plants.

2. Brief history of plant phenological observations

The scientific father of observations of periodical phenomena of plants and animals was *Carl Linné* (1707–1778). Besides his taxonomical works, he observed and recorded the timing of occurrence of birds, flowering of plants, and gave a calendar of nature for Scandinavia.

In the middle of the nineteenth century, two remarkable scientists in Belgium continued a long debate about the aims and methods of observations of periodical phenomena. *Demarrée* and *Rutishauser* (2011) give a detailed description of the correspondence between *Adolphe Quetelet* (1796–1874) and *Charles Morren* (1807–1858). *Quetelet* was physicist and astronomer. He was the founder of the Royal Observatory of Brussels and served as the Permanent Secretary of the Academy of Sciences, Brussels. He initiated a program of systematic observations of periodical phenomena of the vegetation and animal kingdoms in 1841. *Morren* was a professor of botany at the University of Liège and fellow of the Academy of Sciences, Brussels. According to *Quetelet*'s view, only few plants and animals should be observed but at the same time, on a large geographical area. This is very similar to the methods of meteorological observations. *Morren* argued this "too simple" approach and suggested recording the date of occurrence of phenological events. Finally, the discipline of phenology derives from *Morren*'s theory: the goal which proposes the association of the observation of the periodical phenomena is to know ”the manifestation of life ruled by the time.” (*Morren*, 1843).

In Hungary, *Pál Kitaibel* (1757–1817) was the first natural scientist who systematically observed flowering time of plants and explained the differences with climatic reasons. He intended to map flowering times of several agricultural plants; therefore, a circular letter was issued to collect data. Unfortunately, only few response arrived, and therefore, the mapping was not successful (*Both*, 2009).

The relationship of plant phenology and climate was obvious from the beginning; therefore, the observational program of National Meteorological Institutes organized in the middle of the nineteenth century contained also plant phenological observations. Meteorological yearbooks between the years 1871 and 1885 published by the Royal Hungarian Institute for Meteorology and Geomagnetism contain records from 57 locations for 200 plants (not all the plants from each location). Later, in 1910, the Hungarian Geographical Society and in 1934, the Research Institute for Forestry organized observational networks for plant phenological observations.

Organizing and especially maintaining an observational network is not an easy task. There is a need for competent observers and persistent work.

In 1935, the decision of the Agricultural Meteorological Committee of the International Meteorological Organization stated that the same species of plants should be observed in phenological studies everywhere, and that the different stages of development (phitophasis) should be determined uniformly. As *Réthly* (1936) wrote: systematic phenological observations have been carried on for a long time in Hungary by the State Foresters, and have provided much valuable data. The author therefore requests the Hungarian foresters to work according to the above lines in the future.

The collected observations were non-systematic either in space or time. *Dunay* (1984) gave a detailed description on the history of the time by time reorganization of phenological observation network in the Hungarian Meteorological Service. The next starting date of a phenological network maintained by the Meteorological Institute is 1951. The institute prepared the ”Guidelines for phenological observations”. The guidelines described the phases of 75 growing wild plants. The pictures of the guidelines were drawn by *Ms. Vera Csapody*, the famous Hungarian artist and botanist.

The newly established network mainly focused on plants growing wildly. The observation posts of the network were the precipitation stations of the institute. The agricultural plants were observed in 13 places in the agricultural research institutes and in species trial stations. The network was renewed in 1961, when new posts were organized instead of the closed stations. Using the gained experience, a detailed phenological observation program was worked out, and a new guideline, “Guideline for phenological observation of cultivated plants” was issued. The reorganized network had 80 observation stations. The number of observed cultivated plants was 34. Among others, many cereals, rough fodder, cereal fodder, industrial crops, vegetables, and fruits were monitored. Each station observed those species which had importance in their region. Some of the stations observed the phenological phases of cultivated plants; other stations had to monitor fruits or vegetables. The observation program was not restricted to the phenophases only, but it was extended to recording of the agricultural works, the general condition of the plants, and any damage.

The set of the observed growing wild plants were revised, and according to the international practice, the program was renewed again with 36 species. The network monitored 10 treespecies, 10 shrubs, and 16 grass species. Increasing the number of the stations, the phenological network consisted of 120 wildly growing and 80 cultivated plants observations. The Agrometeorological Division submitted a reconstruction plan in 1975 to add plus 33 natural and 236 cultivated plants stations to the network. Within the network, a rapid reporting smaller network was planned with only 30 stations. Taking into consideration the operative demand, a crucial change was carried out in the organization and data transfer system of the network. Instead of professional staff members of the standard meteorological network, the specialists of the MEM-NAK, the Hungarian Plant Protection and Agrochemistry Organization of the Ministry of Agriculture, were recruited into the phenological observation network. Much less mistake was found in the professional agronomist’s observations. The base of the data transfer was the national telex system. In the 80s it was the most rapid and effective tool in the telecommunication. Unfortunately, the observation of natural vegetation was minimized, but the observation of few ”signaling plant” was maintained. Few of them was a good sign of the start of the spring, others have got some economic importance. The new network started its work in 1983 cooperating with the MEM-NAK. This network continued its activity until 2000 when the OMSZ, the Hungarian Meteorological Service closed it because of financial reasons.

According to the international networks, the International Phenological Gardens (IPG) are a European and individual network within the Phenology Study Group of the International Society of Biometeorology. The network was founded in 1957 by *F. Schnelle* and *E. Volkert*. The current network ranges 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. It consists of 89 gardens in 19 European countries. The philosophy of this network is quite different than the Hungarian’s one. In all gardens, genetically identical trees and shrubs are planted in order to make large-scale comparisons among the timing of different developmental stages of plants. Recently, the coordination of this network belongs to the Humbolt University of Berlin (*Chmielewski*, 1996).

Among the most important and recent phenological activities at international level, there is the youngest phenological network of the United States. After two years of preparatory period, in 2007 it started its activities based mainly on volunteer observers (*Betancourt et al.*, 2007).

3. Phenological research work

The use of phenological observations is manifold. For scientific investigations, for planning and consulting tasks as well as in daily practice, phenological data are required. Examples for the application of phenological data are investigations of the impact of climate changes on plants, calibration of remotely sensed data, use of these data in yield-, growth-, or hydrological models, determination of regions with high frost-risks for fruit-tree growing, and the monitoring of environmental changes. Since the end of the 1980s, the demand for phenological observations increased substantially. Mainly, the rise in air temperature in the previous decades and the clear phenological response by plants led to this increased interest in phenological data.

3.1. Phenology in crop models

The ability to estimate the time required for a crop to pass through its various stages of development to maturity is useful in at least one other important way - it assists greatly in estimating crop yield. The history of phenological modeling goes back at least as far as 1735. It was then that *Reaumur* (1735) suggested that the time required for plants to complete a phase of their development could be more accurately estimated from temperature sums than from calendar days. Although there are many variations of the original concept, most methods of estimating phenological development still use this relatively simple approach.

Phenological modeling inevitably involves mathematical equations that express the rate of change in life stage as a function of environmental variables, such as temperature, humidity, photoperiod, and radiation. These equations are usually the product of regression analyses of experimental data (*Shaykewich*, 1995).

The models can be different according to:

- the phenophases taken into consideration,
- environmental variables (temperature, day-length, vernalization, etc.),
- the form of functions describing the effect of the environmental variables (linear, non-linear),
- the structure of the model (additive, multiplicative).

The models are always plant specific. They contain several plant specific parameters which can be different even for the different varieties.

Example 1: In the CERES-Maize model (*Jones* and *Kiniry*, 1986), phenological development is calculated as a function of growing degree days or daily thermal time (*DTT*) with a base temperature of 8 °C. The maize phenological phases used in the model are described in *Table 1*. The model assumes that the rate of development increases linearly above the base temperature up to 34 °C and then decreases linearly to zero as temperature increases from 34 to 44 °C. Similarly, rates of leaf initiation and leaf-tip appearance are assumed to change linearly in these two ranges of temperature. Photoperiodic induction is assumed to decrease with increasing photoperiod for photoperiods longer than12.5 hours. The number of days of tassel initiation delay for each hour increase in photoperiod is assumed to be a constant for any given photoperiod-sensitive cultivar. The total number of leaves is determined from the number of leaf primordia initiated between seedling emergence and tassel initiation. Date of tassel initiation is determined using both *DTT* with a base temperature of 8 °C and photoperiod. Silking or end of leaf growth is determined from total leaf number and the rate of leaf-tip appearance.

Table 1. Phenological phases used in CERES-Maize model.
(Source: *Jones* and *Kiniry*, 1986)

Phase No.	**Description**
1.	Seedling emergence to end of juvenile phase
2.	End of juvenile phase to tassel initiation (photoperiod-sensitive phase)
3.	Tassel initiation to silking
4.	Silking to beginning of effective grain-filling period (lag phase)
5.	Effective grain-filling period
6.	End of effective grain-filling period to physiological maturity (black layer)
7.	Before sowing (fallow)
8.	Sowing to germination
9.	Germination to seedling emergence

Example 2: Wheat phenological model of *Wang* and *Engel* (1998) is a multiplicative non-linear model. The first step in using the WE model is to calculate the daily rate of plant development (r). There are two main developmental stages: vegetative phase from emergence until anthesis and reproductive phase from anthesis until physiological maturity. The developmental stage (DS) is then calculated by accumulating the daily development rate values (i.e., at a 1 day time step, $DS=\Sigma r$). Other developmental stages in the vegetative phase are 0.4 at spikelet initiation, 0.8 at late booting, and 0.88 at awns first visible.

The model equationfor the vegetative phase is

$$r = R_{max,v} f(T) f(P) f(V), \tag{1}$$

while for the reproductive phase it is

$$r = R_{max,r} f(T), \tag{2}$$

where r is the daily development rate (per day), $R_{max,v}$ and $R_{max,r}$ are the maximum development rate (per day) in the vegetative and reproductive phases, and $f(T)$, $f(P)$, and $f(V)$ are temperature, photoperiod, and vernalization response functions, varying from 0 to 1.

The temperature response function is

$$f(T) = \frac{2(T - T_{min})^{\alpha}(T_{opt} - T_{min})^{\alpha} - (T - T_{min})^{2\alpha}}{(T_{opt} - T_{min})^{2\alpha}}, \tag{3}$$

$$\alpha = \frac{ln 2}{ln[(T_{max} - T_{min})/(T_{opt} - T_{min})]}, \tag{4}$$

where $T_{\min}$, T_{opt}, and $T_{\max}$ are the cardinal temperatures for development (minimum, optimum, and maximum), and T is the mean daily temperature calculated from the 24 h temperature.

For the vegetative phase, $T_{\min}$, T_{opt}, and $T_{\max}$ were 0 °C, 24 °C, and 35 °C, and for the reproductive phase they were 8 °C, 29 °C, and 40 °C, respectively (*Xue et al*., 2004).

The photoperiod response function is

$$f(P) = 1 - e^{-\omega(P - P_C)}, \tag{5}$$

where P is the actual photoperiod (h), P_c the critical photoperiod (h) below which no development occurs, and ω is a cultivar specific photoperiod sensitivity coefficient [h^{-1} g]. Values of P_c and of ω are variety specific.

The vernalization response function:

$$f(V) = min\{1; max[0; (V_n - V_{nb})/(V_{nd} - V_{nb})]\}, \tag{6}$$

where V_n is the effective vernalization days, V_{nd} is the number of effective vernalization days for the plant to be fully vernalized, and V_{nb} is the minimum effective vernalization days, i.e. development begins only after a minimum value of V_{nb} has been reached (*Weir et al.*, 1984).
The functions max and min in Eq. (6) represent the maximum and minimum values in a string of numbers, respectively. The effective vernalization days, V_n, is calculated from sowing as

$$V_n = \sum fv_n(T), \tag{7}$$

where $fv_n(T)$ is the daily vernalization rate (per day), calculated using Eqs. (3) and (4) with the cardinal temperatures for vernalization ($T_{\min,vn}$, $T_{\mathrm{opt},vn}$, and $T_{\max,vn}$) being −1.3, 4.9, and 15.7 °C (*Porter* and *Gawith*, 1999). Both V_{nb} and V_{nd} are cultivar dependent.

These types of plant phenological models are always plant specific. Parameterization of the model is possible on experimental plots or in growth chambers. Whenever you want to develop phenological model for a native plant (especially for trees and shrubs), you should use long-time data series and the physiological parameters should be estimated on statistical ways.

3.2. Phenology in climate change studies

In the 1990s, the interest in phenological research and thus, the demand for phenological observations has increased substantially. Mainly, rising air temperatures in recent decades and the clear phenological response of plants and animals to this increase have caused the growing interest. Many studies have shown that the timing of life cycle events is able to provide a good indicator for climate change impacts (*Schwartz,* 1994; *Menzel et al.*, 2006; *Chmielewski* and *Rötzer*, 2001, 2002). The timing of phenological phases depends on numerous environmental conditions: temperature, precipitation, soil type, soil moisture, and insolation. However, in mid- and high latitudes, with vegetation-rest (dormancy) in winter and active growing period in summer, air temperature has the greatest influence on phenology (*Fitter et al*., 1995; *Sparks et al*., 2000; *Chmielewski et al*., 2005). A comprehensive understanding of species phenological responses to global warming will require observations that are both long-term and spatially extensive. Long-term data series deriving from the same place are rare. One of these rarities is the data series of cherry tree flowering in Kyoto, Japan (*Aono* and *Kazui,* 2008), in which the first records came from the ninth centuries. In England, phenological events of various plants and animals observed since the 18th century have been reported as Marsham's phenological data series (*Margary,* 1926). In Geneva, Switzerland, the leafing date of the chestnut tree has been observed since 1808, and these records have been used to show climatic warming since the early 19th century (*Defila* and *Clot,* 2001). In

Hungary, there is unique series of St. George Day's wine shoot book in Kőszeg, in which every year since 1740 wine shoot captures notes and drawings are included. The work is still continuing, so more than 205 years of data series available (*Kiss*, 2009; *Kiss et al*., 2011).

Monitoring phenological phases is carried out in many European countries. Each country has its own database, in some cases still on paper, mostly on databank-systems, going back to the 1950s in many cases.

After a period of reduction of the density of phenological networks and even cancelling all national observations in some countries in the 1980s, new interest in phenology grew in the following decade due to the new interest in climate change issues. In 2004, a new COST (European Cooperation in the Field of Scientific and Technical Research) Action was launched on European level. The basic idea of the Action was as a starting point to build a reference data set of selected species and phases that have been observed in European countries over a common reference period of at least one decade but preferably longer, using the BBCH code which was applied on phenophases observed in different countries by the German Weather Service. The project ended in 2009. According to the final report of COST 725 (*Koch et al*., 2009) using 125,000 observational series of 542 plant and 19 animal species in 21 European countries for the period 1971–2000, the aggregation of the time series revealed a strong signal across Europe of changing spring and summer phenology: spring and summer exhibited a clear advance by 2.5 days/decade in Europe. Mean autumn trends were close to zero, but suggested more of a delay when the average trend per country was examined (1.3 days/decade). The patterns of observed changes in spring (leafing, flowering, and animal phases) were spatially consistent and matched measured national warming across 19 European countries; thus, the phenological evidence quantitatively mirrors a regional climate warming. The COST 725 results assessed the possible lack of evidence at a continental scale as 20%, since about 80% of spring/summer phases were found to be advancing.

In the IPCC AR4 WG II report (*Parry et al*., 2007), the COST 725 study is one of the major contributions for the assessment of observed changes and responses in natural and managed systems. As a continuation, the chair of COST 725 submitted a 5 years project proposal PEP 725 (Pan European Phenological database), which was accepted by EUMETNET and launched in 2010. COST 725/PEP 725 is also being one of the leading partners of the new GEO-task: Global Phenology Data. Together with the USA National Phenology Network and the University of Milwaukee, COST 725/PEP 725 will coordinate the collection of in-situ phenology observations and expand existing observing networks, identify and generate satellite-derived phenological/temporal metrics, and test models for describing the phenological characteristics of natural and modified ecosystems. Changes in vegetation phenology impact biodiversity, net primary productivity, species distribution, albedo, biomass, and ultimately, the global climate.

4. Phenology from the space

The guides for plant phenological observations give detailed descriptions about morphology of different phenophases concerning to individual plants. This method is applicable in phenological gardens, where plants are the same or planted in the same place year by year, and they are monitored day by day. If a larger area of plant stands should be characterized by the phenological stages, difficulties arise because of the variability of individuals. In this case the percentage of plants having that specific phase should be estimated. This is a significant source of bias.

Remote sensing phenology, the use of satellites to track phenological events can complement ground observation networks. Satellites provide a unique perspective of the planet and allow for regular, even daily, monitoring of the entire global land surface.

Because the most frequently used satellite sensors for monitoring phenological events have relatively large "footprints" on the land surface, they gather data about entire ecosystems or regions rather than individual species. Remote sensing phenology can reveal broad-scale phenological trends that would be difficult, if not impossible, to detect from the ground. Moreover, because data collection by satellite sensors can be standardized, the data are reliably objective. Obviously, remote sensing data are not the traditional phenological phases but they are reflectance (ρ) in different spectral channels. The status of the vegetation is in close connection with its reflectance, especially in the near infrared and red spectra; therefore, the normalized difference vegetation index, (NDVI) has often used to characterize the vegetation status (*Reed et al*., 1994):

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}}. \tag{8}$$

Analyzing the seasonal curve of NDVI, the time of onset and the end of the vegetation season can be taken when NDVI reaches a threshold value (0.3) (*White et al*., 2009; *Botta et al*., 2000; *Jolly et al*., 2005).

A bit more sophisticated the enhancedvegetation index (EVI) has an advantage over NDVI, because EVI includes a blue band, which allows residual atmospheric contamination and weight to be taken into account, compensating for the variable soil background reflectance (*Liu* and *Huete*, 1995; *Huete et al*., 2002; *Churkina et al*., 2005).

$$EVI = G \times \frac{\rho_{nir}/\rho_{red} - 1}{\rho_{nir}/\rho_{red} + \left(C_1 - C_2 \times \rho_{blue}/\rho_{red}\right) + L/\rho_{red}}, \tag{9}$$

where L is a soil adjustment factor, and C_1 and C_2 are coefficients used to correct aerosol scattering in the red band by the use of the blue band. ρ_{blue}, ρ_{red}, and ρ_{nir} represent reflectance at the blue (0.45–0.52μm), red (0.6–0.7μm), and near-infrared (NIR) wavelengths (0.7–1.1μm), respectively. In general, G=2.5, C_1=6.0, C_2=7.5, and L=1.

Temporal variation in EVI data are modeled using piecewise sigmoidal models. Each growth cycle is modeled using two sigmoidal functions: one for the growth phase, one for the senescence phase. To identify phenological transition dates, the rate of change in the curvature of the fitted logistic models is used. Specifically, transition dates correspond to the times at which the rate of change in curvature in the EVI data exhibits local minima or maxima. For each growth cycle, four phenological transition dates are recorded based on the approach described above. The corresponding phenological transition dates are defined as the onset of greenness increase, the onset of greenness maximum, the onset of greenness decrease, and the onset of greenness minimum.

Both NDVI and EVI data are available from MODIS placed at Terra and Aqua satellites. Data are provided by NASA Land Processes Distributed Active Archive Center (*NASA LP DAAC*, 2011). Our future plan is analyzing EVI data for different regions of Hungary for the last ten years. The EVI data on June 26, 2011 is shown in *Fig. 1* for Hungary. For a selected area of 5 × 5 km around Szenna (46°18.47'N, 17°43.95'E), time series from April to August, 2011 of EVI is presented in *Fig. 2*. The average seasonal curve for one pixel selected from the area mentioned above using data from 2003–2011 is shown in *Fig. 3*.

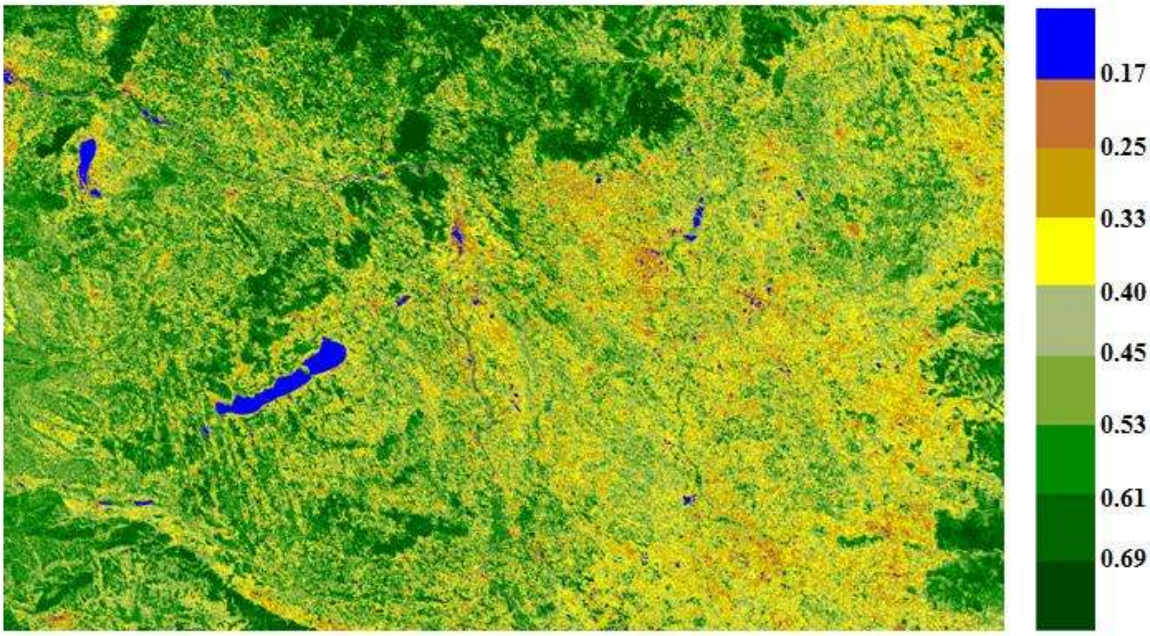

Fig. 1. Enhanced vegetation index (EVI) for the area of Hungary on June 26, 2011. Larger EVI indicates more developed vegetation.

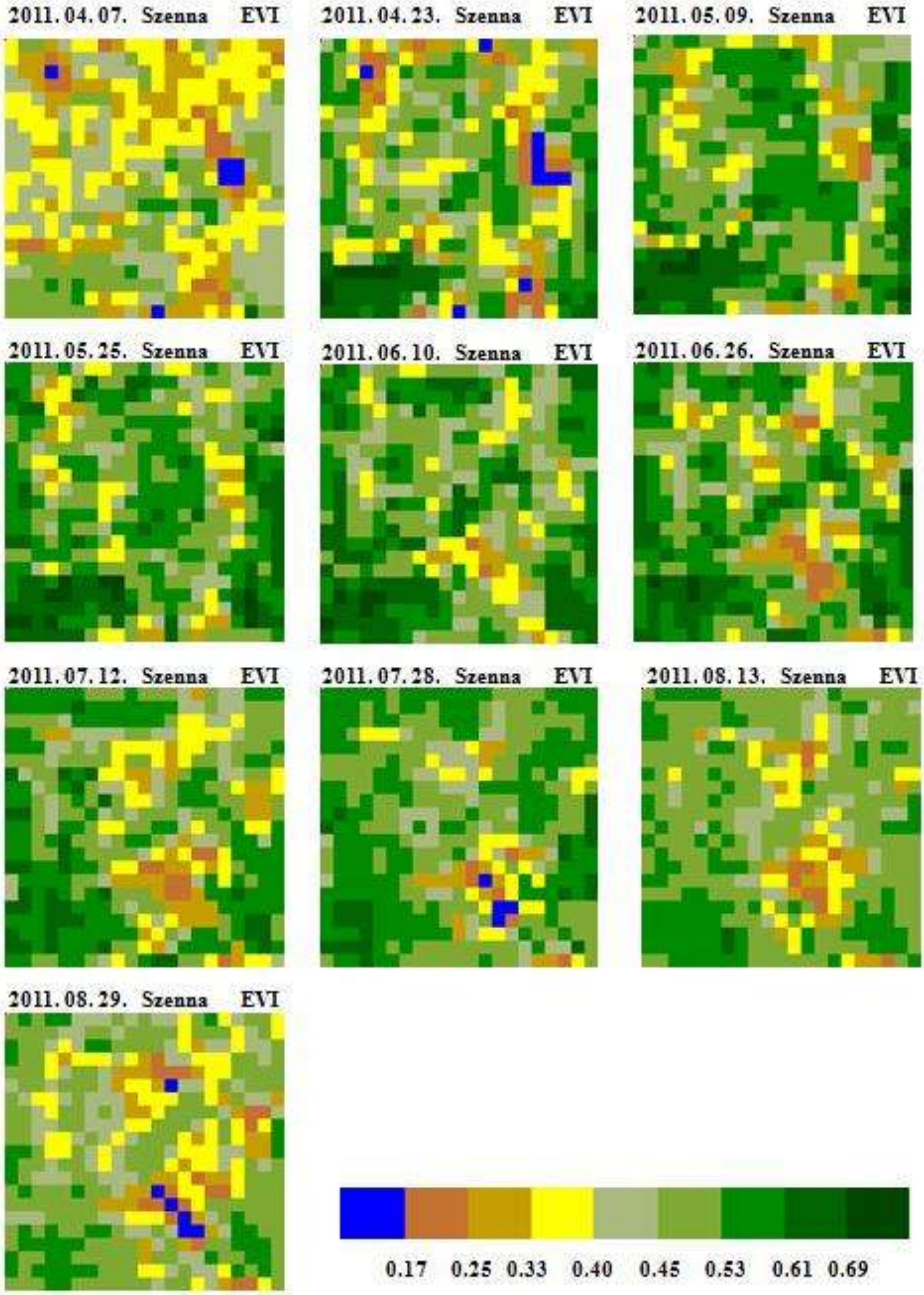

Fig. 2. Seasonal development of vegetation in a selected area according to EVI. The site of observations is a 5 km x 5 km area around Szenna (46°18.47'N, 17°43.95'E) between April and August, 2011.

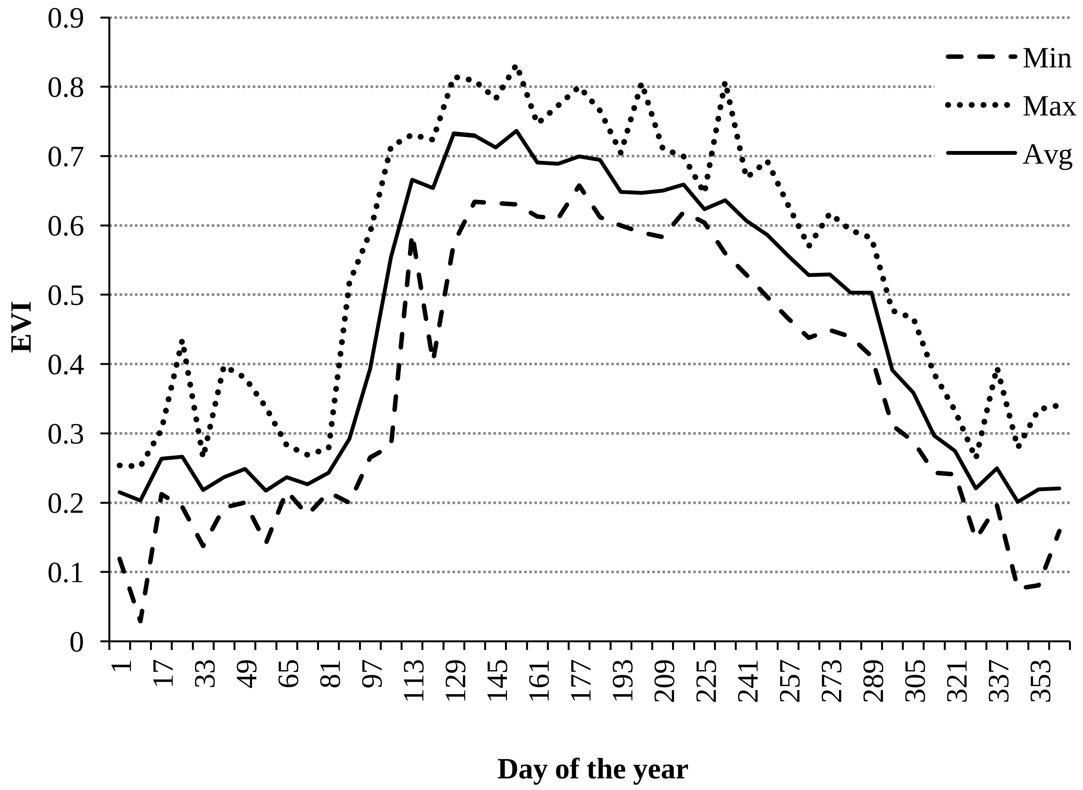

Fig. 3. Seasonal curve of EVI averaged for the years 2003–2011 for a selected pixel.

5. Conclusion

In the last two decades, climate change became a prevailing scientific paradigm, therefore, relating areas like phenology has been refocused. Searching for old phenological records, developing phenological models and new observation techniques applicable to track responses of vegetation to changing environment, and revealing interrelationships between biosphere and atmosphere are interesting tasks. New projects have been launched worldwide both on national and international levels to study plant and animal phenology. Reorganization of observation networks and collecting data is a big deal again. Remote sensing techniques offer new opportunities for comprehensive evaluation of processes taking place in biosphere.

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