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Using of long-term phenological observations of SHMI and NFC for validation of Regional Phenology Model for European beech

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Abstract

This study describes the methods and results of the validation of Regional Phenology Model based on NDVI (Normalized Difference Vegetation Index) from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite images for European beech (Fagus sylvatica L.). The time series of phenological observation of regional phenological observation sites of SHMI (Slovak Hydrometeorological Institute) for years from 2000 to 2009 and permanent monitoring plots of NFC (National Forest Centre) for 2002 – 2009 was used to validate the date of start of five main spring and autumn phenological events.

The most accurately were derived the phenological events the first leaves, full leafing and the beginning of colouring of leaves. The resulting duration of full foliage was derived with an average error of ± 4.2 days (r = 0.84). Date of onset of phenophases bud break and full colouring of leaves, determining the duration of the entire growing season, were derived with a systematic negative (budbreak), respectively. positive error (full colouring) which increases with increasing altitude. It resulted in an overestimate of the duration of the growing season by an average of 26 days. Possible causes of the differences in the timing of the individual phenophases and their duration are discussed in this paper.

Key words: Regional Phenology Model, MODIS, NDVI, European beech

Introduction

Phenology examines the timing of important, periodically repeated phases of living plants, so-called phenological phases that depend on the complex environmental conditions, particularly the weather and climate. Phenology as a science is not limited to description and dating of phenological events, but it also study and explain the effects caused by these phenomena (Larcher 1988).

After bud break there is going out a rapid growht of assimilation apparatus of trees. This phenophase is called leaf unfolding. Period of photosynthetic activity of leaves is finished during the next event, which is the colouring of leaves. As the final phase of phenological calendar we can designate the leaf fall.

Phenological observations are also relevant in terms of determining the total length of the growing season of forest trees. After the compleat development of foliage the important period begin; the mature leaves have maximal photosynthetic activity. The duration of phenophase called full foliage, along with other factors, is crucial for the overall production of plants (Hicks and Chabot 1985). The duration of the period of full foliage is important not only in terms of overall growth and production of forest trees, but can affect also the quantity and quality of throughfall precipitation. The duration of vegetation season from bud break to leaf fall for the broadleaved species birch, beech and oak ranges between 5.5 to 6 months (Chalupa 1969).

Satellites based detection of biophysical and structural characteristics of forest stands allows to improve knowledge of the response of forest ecosystems to changing environmental conditions. Launch of satellites Terra and Aqua (NASA Earth Observation Satellites System) with spectroradiometer MODIS (Moderate Resolution Imaging Spectroradiometer) opened up new possibilities for continuous and global monitoring characteristics of forest ecosystems, such as: the normalized vegetation index (NDVI), leaf index (LAI) and the share photosynthetically active radiation absorbed by vegetation (FPAR). The above characteristics are important identifiers of health and ecological conditions of the forest, and are used as inputs to the phenological models (Zhang et al., 2003). Regional Phenological Model is based on evidence that there is a close relationship between the ecophysiological measurements (NDVI, LAI, FPAR) in forest stands and reflectance, measured by satellite sensors (Shabanov 2003 Gobron et al., 2005). Results from terrestrial measurements are used for validation and parameterisation of outputs of remote sensing data (Cohen et al., 2003).

The aim of this study was to describe the methods and results of the validation of Regional Phenology Model based on NDVI (Normalized Difference Vegetation Index) from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite images for European beech (Fagus sylvatica L.). The time series of phenological observation of regional phenological observation sites of Slovak Hydrometeorological Institute for years from 2000 to 2009 and permanent monitoring plots of National Forest Centre for 2002 – 2009 was used to validate the date of start of five main spring and autumn phenological events.

Materials and methods

Construction of phenology model

The modeling phenological development of forests means the prediction of the main phenological events. The annual development of vegetation index was analyzed using the sigmoidal logistic curve (Fisher 2007).

$$v(t) = v_{\min} + v_{amp}\left(\frac{1}{1+e^{m_1+m_2t}} - \frac{1}{1+e^{m_3+m_4t}}\right) \quad [1]$$

Parameters v_{min} and v_{amp} correspond to the minimum value of the vegetation index (NDVI) and amplitude; parameters $m_{1,2,3,4}$ control the shape and slope of the growth (spring) and descending (autumn) phase. Phenological curve was used to derive the date of start of key phenological events. These were derived from the curve by calculating the derivatives of the function and its curvature.

Phenological observations of permanent monitoring plots and spatial transects were used to verify the hypothesis that the extreme values of rate of change of curvature (a local minimum and maximum) are related to the onset of selected phenological event.

Phenological observations

Phenological observations were carried out at 24 regional phenological monitoring stations of SHMI with occurrence of beech and three permanent monitoring plots of NLC (in the following text mentioned as the phenological stations).

Phenophases of broadleaved trees were evaluated according to the scale of the manual for phenological observations of European monitoring system (Preuhsler 1999) and the scale developed by the Slovak Hydrometeorological Institute (Braslavská and Kamenský 1996).

The onset of phenological event is considered as the day when more than 50% of the assessed trees achieved given event. The duration of phenophase was determined by the number of days between the onset of two successive phenological events. Observations were made individually, using binoculars. At each monitoring plot was rated 10 level subjects.

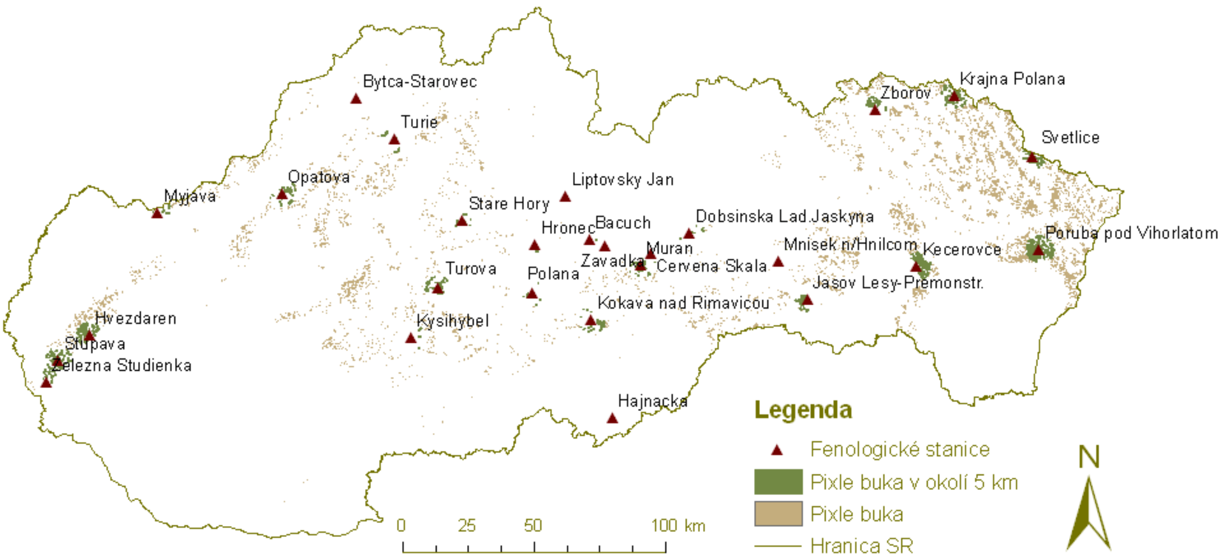

Figure 1 The spatial distribution of phenological stations and analyzed forest stands with dominant contribution of beech for whole territory of Slovakia and in the vicinity of phenological stations

Study area and data source

Phenological curve was calculated for beech stands in Slovakia. Pixels of beech (Fig. 1) were selected by combination of two methods - classification of tree species composition from satellite images (Bucha et al. 1999) and the selection according to data of the distribution of beech forest stands in the description JPRL (unit spatial distribution of forest). The boundary pixels and pixels with representation of beech less than 40% were excluded.

The pixels classified as beech within 5 km radius from each phenological stations were selected for analysis. For validation of RFM (Regional Phenology Model) we used the long-term observation of 24 phenological stations of SHMI, 2 permanent monitoring plots of NLC and 3 transects with the occurrence of beech (only for the years 2009-2010). For each selected group of pixels was detected mean altitude and mean values of the onset of assessed phenological events, derived using phenological curve for each year in the period 2000 - 2009 (in the case of permanent monitoring plots NLC period from 2002 to 2009).

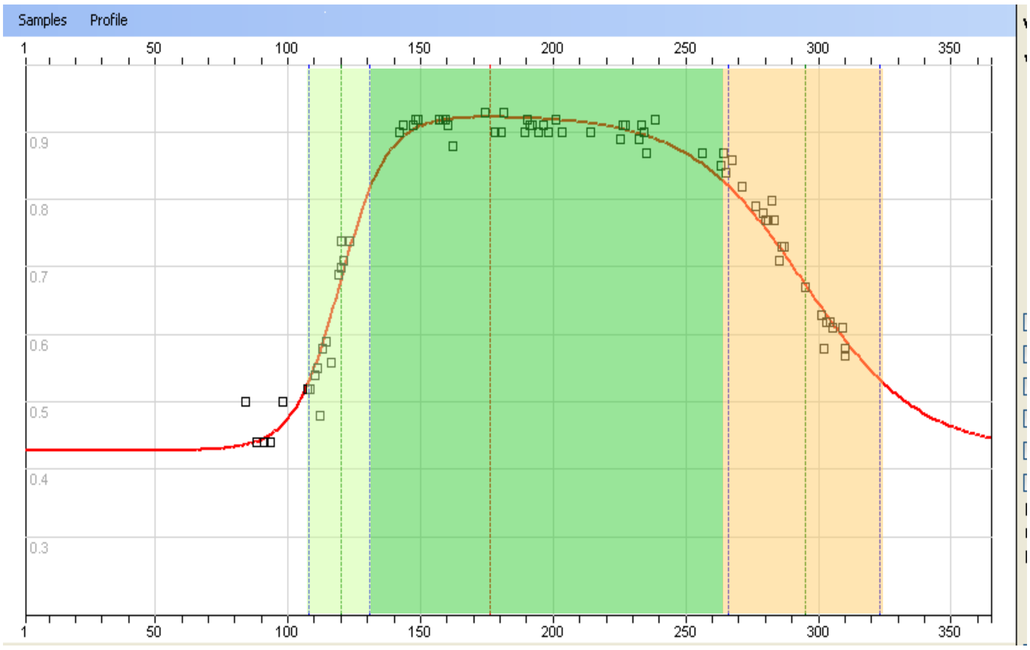

Figure 2 Logistic sigmoidal function with associated days of phenological events that determined phenological phases i) leaf unfolding (light green), ii) full foliage (dark green), iii) colouring and fall of leaves (orange)

Results and discussion

Annual course of NDVI for all pixels classified as beech in the period 2000 - 2010 was modeled using a sigmoidal function in the software Phenological Profile ©. This software allows you to calculate extremes in spring and autumn phenological phases, as well as to determine the days when these extremes occur (1st and 2nd derivative). From extreme value interpolation function and their associated date were determined three basic functions of phenological phases: i) leaf unfolding (spring phase, growth period), ii) full foliage (summer phase) and iii) colouring and leaf fall (autumn phase, declination period) (Fig. 2).

Based on long-term phenological observations at permanent monitoring sites NLC and the newly established spatial transect the extreme values of interpolation functions (and the day when they occured) was associated with the onset of each phenological event (Fig. 2):

a) bud break (the beginning of the acceleration in the growth period)
b) the first leaves (maximum acceleration in the growth period)
c) full leafing (the beginning of the decline in the growth period)
d) beginning of colouring of leaves (start of acceleration in the decline period)
e) full colouring of leaves (maximum acceleration in the decline period)

The timing of individual phenophases subject to considerable interannual variation. It is influenced by the meteorological conditions during the current year (air and soil temperature, the occurrence of late frost, moisture availability, etc..).

Between the date of onset of the individual phenological events and altitude there is moderate non-linear relationship. The onset of spring phenophases delays with increasing altitude, the onset of autumn phenophases decreases with altitude, except of the sites with low altitude where the dry conditions at the end of vegetation season probably cause premature yellowing. The length of the growing season of European beech decreases with altitude.

Validation of regional phenology model

Data derived from regional phenology model (RFM) were validated using data from long-term observations on the permanent monitoring plots and regional phenological stations. For validation, we used data obtained from multiple projects and programs of Slovak Hydrometeorological Institute and National Forestry Centre (Climatological Service of SHMI, ICP Forests, Forest Focus, FutMon).

For each pixels group within the 5 km radius from each phenological station, the median of the date of onset of five phenological events was calculated (derived from NDVI curve). We excluded stations without any pixel classified as beech in vicinity (Hajnáčka, Liptovský Ján, Bytča). Using higher number of pixels around each phenological station can eliminate the high spatial variability at the onset of each phenological phases in a relatively small area, which could have a negative impact on the comparison of data from ground-based observations and data derived from regional phenological model and consequential interpretation of results (Fischer et al. 2006).

Basic set (all pixels classified as beech) and the sample set (pixels within a radius of 5 km from the phenological stations) have normal distribution of frequencies according to altitude. Based on the frequency distribution the sample set can be considered sufficiently representative for the territory of Slovakia. Frequency distribution according to altitude in the sample set in the vicinity of phenological stations does not exactly match distribution of phenological stations; that could be one of the sources of uncertainty during validation (Fig. 3).

During the validation we evaluated i) the accuracy of the onset of each phenological event, ii) the duration of phenological phases and iii) the duration of full foliage and the growing season.

We have identified several potential sources of uncertainty derivation regional phenological model.

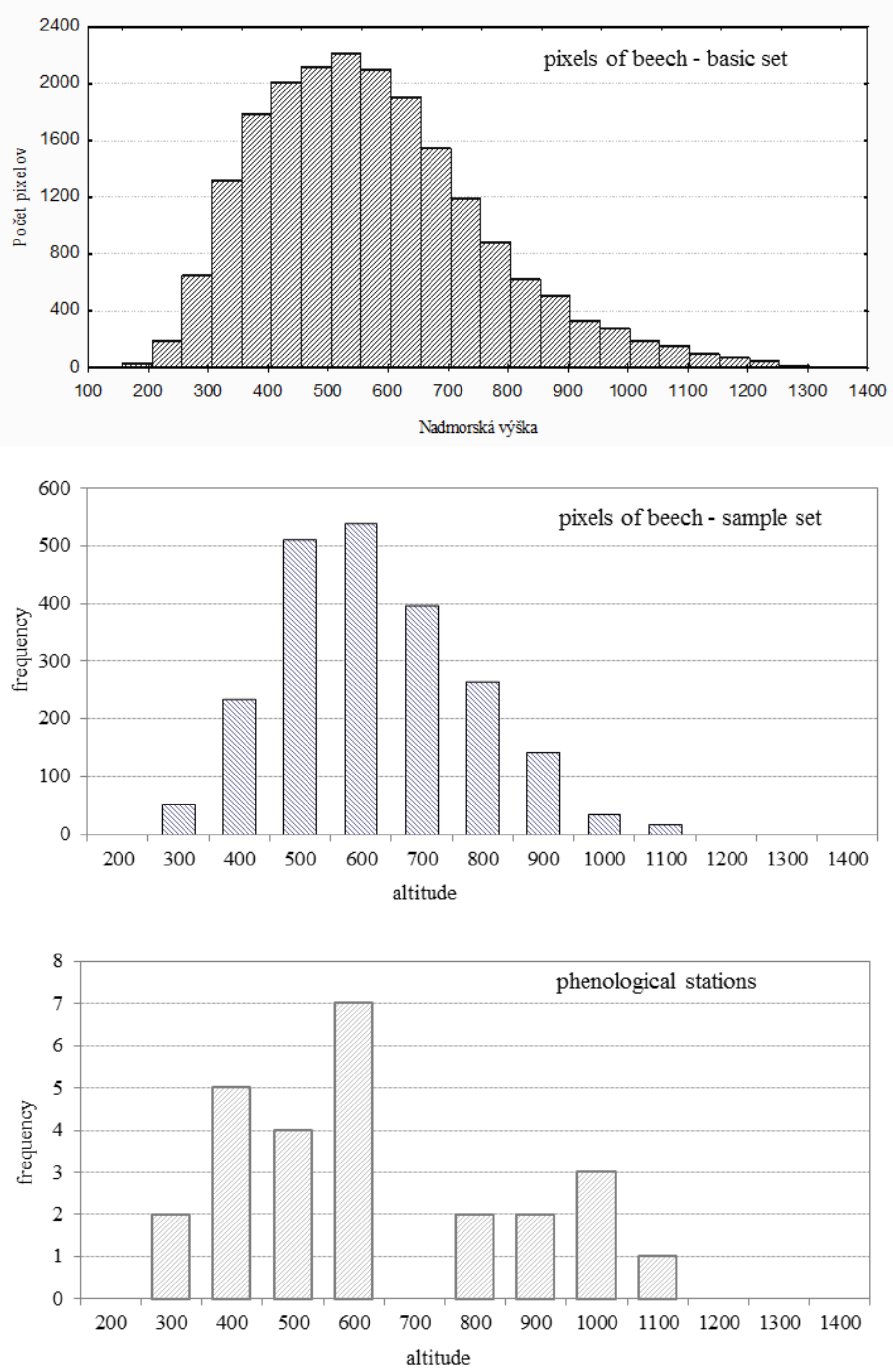

Figure 3 The distribution of frequencies according to altitude for all pixels classified as beech, pixels within 5 km radius from phenological stations and for phenological stations

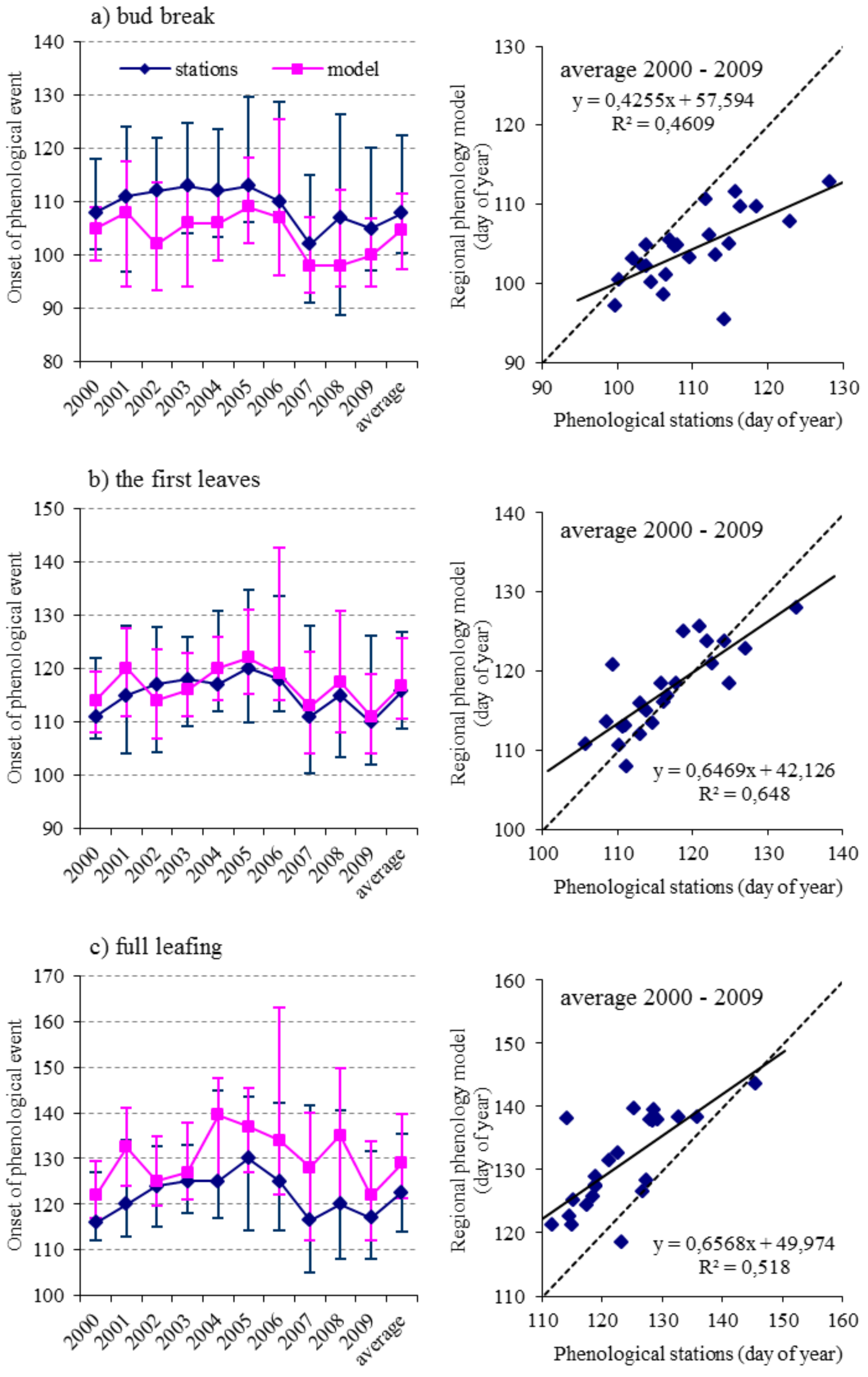

Figure 4 Average day of onset of spring phenological events (bud break, the first leaves, full leafing) during 2000 - 2009 and their correlation between phenological observation and data derived from RFM (error bars represent 5-95 percentile of values)

Bud break

Bud break derived from RFM occurs, on average, 5.6 days earlier than the observed bud break (Fig. 4a). The absolute difference between observed and derived values increases with altitude.

There are more possible reasons of the observed differences. One of possible reason is the occurrence of understory trees and bushes and their earlier onset of leaves unfolding comparing to the observed trees in canopy. For beech forest stands there is typical the occurrence of spring herbs, so-called spring heliophytes. Like in the case of understory trees, a slight shift of terms in comparison with MODIS data may be due to earlier onset of ground vegetation compared to the tree level, a strategy known as phenological escape (Brandýsová and Bucha 2012).

The first leaves

The first leaves is the most accurate derived phenological event, with an average error of 0.9 days, compared with the ground-based observations in phenological stations (Fig. 4b). It is also the phenological event that is in some phenology models considered to be the onset of the growing season (Fisher et al., 2007).

Full leafing

This phenological event was derived with a systematic error, in the average delay of 7.6 days (Fig. 4c).

Phenological event full leafing of deciduous trees is defined as a state where already all individuals in the group have leaves, leaves are light green, but still smaller than mature leaves (Braslavská and Kamenský 1996). After leaf unfolding, the assimilation apparatus continues to growth rapidly, changing its quality, which affects the reflectance. Enlarging of leaves occurs (while the increase of leaf area) even after the phenological event full leafing. According to observations of seasonal changes in leaf area index (Pavlendová 2009) we can consider this derived phenological event as a state when the main growth of assimilation apparatus was finished.

Course and duration of leaves unfolding (spring phase, growth period)

According to the results derived from MODIS RFM the length of this phenophase have increased with altitude, this increas does noc result from observations of phenological stations.

The duration of the spring phenophase leaves unfolding was overestimated as a result of earlier determination of bud break and later determination of full leafing in RFM. On average, in absolute values the overestimation was 13.3 days (12.6 vs. 25.9 days), that is over 100%.

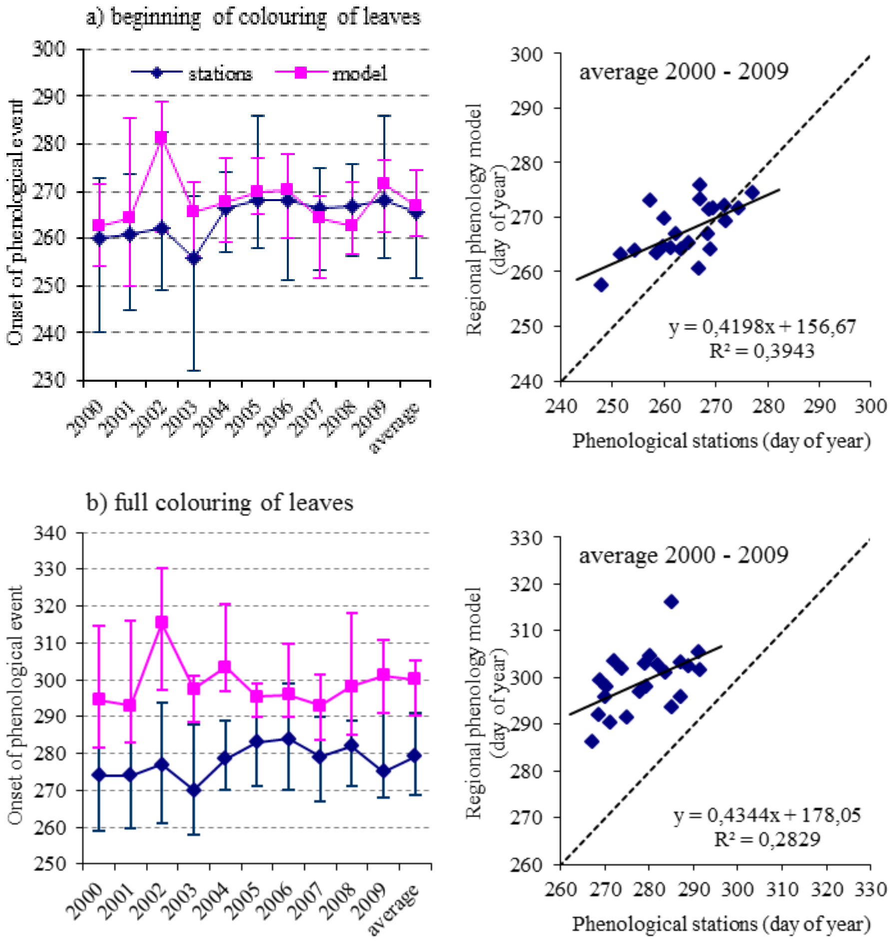

Figure 5 Average day of onset of autumn phenological events (the beginning of colouring of leaves and full colouring of leaves) during 2000 - 2009 and their correlation between phenological observation and data derived from RFM (error bars represent 5-95 percentile of values)

Beginning of colouring of leaves

Phenological event the beginning of colouring of leaves has been derived with a random error, on average with a delay of 3.3 days (Fig. 5a).

Onset of this event decreases with altitude (beginning earlier), with the exception of the sites with low altitude that probably manifest the impact of drought on premature yellowing. The onset of leaves colouring derived from RFM lasts significantly shorter period, compared to the observations of phenological stations (Fig. 5a).

Full colouring of leaves

Full colouring of leaves is the least accurately derived phenological event. It was derived with a systematic error, 20.2 days in average (Fig. 5b).

Major cause of inaccurate derivation of full colouring of leaves, as well as other autumn phenophases (start and end of leaf fall) can be considered the way there are changes in the reflectivity autumn: reflectance gradually declines over the colouring, leaf fall and later, to a value before starting growing season. Yellow and dead leaves still on the trees is not possible to distinguish using satellite images from fallen leaves, where their gradual decomposition is influenced by several factors, especially moisture.

The course and duration of leaves colouring (autumn phase, declination period)

According to the results derived from MODIS RFM the length of the phenophase leaves colouring increases with altitude, this increas does noc result from observations of phenological stations. Significant delay of phenological event full colouring of leaves derived from RFM resulted in overestimate of the duration of the first part of autumn phenophase – leaves colouring.

The difference between the length of the events derived from RFM and the observed values at phenological stations averaged in absolute terms 15.6 days (30.5 vs. 14.9 days), in relative terms it is again more than 100%.

The duration of the growing season

Currently, several approaches are used in the calculation of the duration of the growing season, a uniform definition of the growing season does not exist (White et al. 1997).

Part of phenological models defined beginning and end of growing season (onset and offset) as a half maximum at the sigmoidal curve for NDVI (Fisher 2007) or LAI (Kang et al. 2003, Hanes & Schwartz 2010), the others identify the onset and offset of growing season as the point of greatest changes at the logistic curve (Zhang et al. 2003). Some models that use phenological data define the vegetation season as the period from bud break to full colouring of leaves, however, thay require the data about the duration of the ascending (spring) and descending (autumn) phenophase (eg. DO3SE).

The definition of the duration of the growing season differs according to requirement of the models, balances and evaluations with input of the phenological data (hydrological, production model, gas flux, nutrient balance, etc..).

The main advantage of RFM is that it allows to derive timing of all phenological events and can calculate the length of growing season according to the required definition.

In the first phase, we calculated the length of growing season as the period between budbreak and full colouring of leaves (Fig. 6). The length of the growing season derived from RFM was systematically overestimated by 26.1 days in average (standard error 27.9 days).

The duration of full foliage is part of the growing season crucial for the overall production. It was derived from RFM with the random error in comparison with terrestrial phenological stations, 4.2 days shorter in average (standard error 7.6 days) (Fig. 6).

The results show that the regional phenology model can quite accurately derive the timing of spring phenological phases, as well as the duration of full foliage. We detected higher errors for determination of autumn phenophases, especially the full colouring of leaves. Similar results reported Stöckli et al. (2008), who used phenology prediction model with high accuracy in derivation of onset of the growing season, but the model was weak during determination of offset of growing season. Problems with modelling of offset of growing season for beech treesw reported also Richardson et al. (2006).

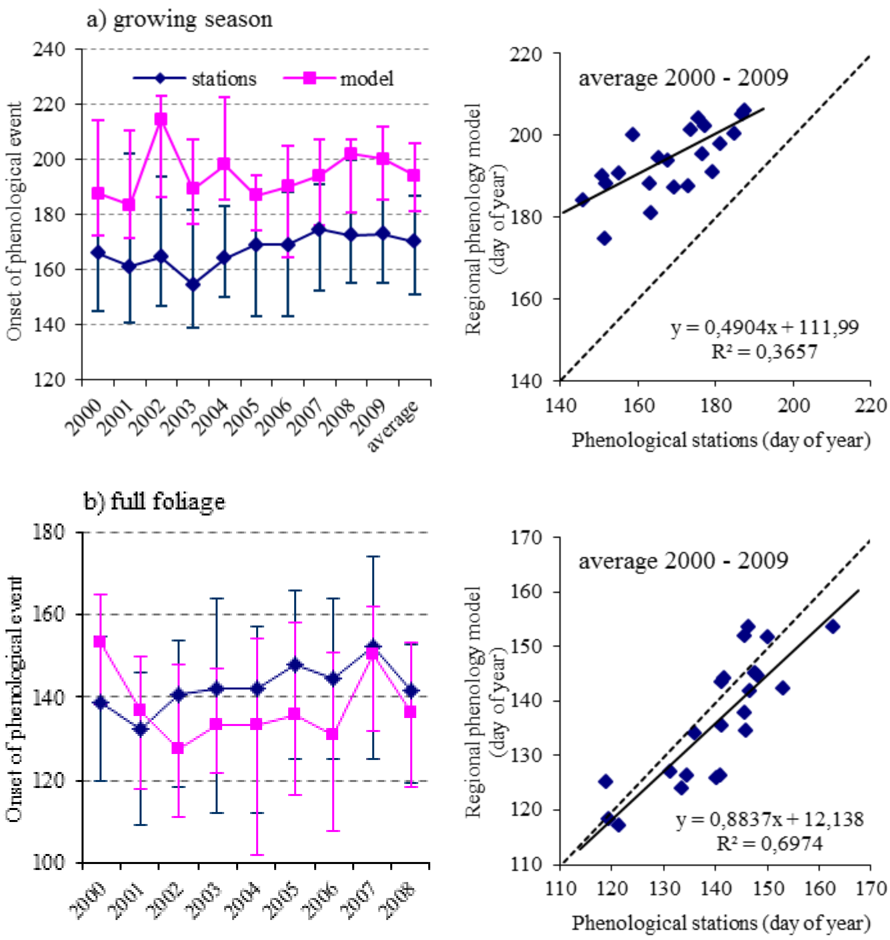

Figure 6 Average duration of the observed and derived growing season (growing season and full foliage) during 2000 - 2009 and their correlation between phenological observation and data derived from RFM (error bars represent 5-95 percentile of values)

Conclusion

The timing of five phenological events based on NDVI curves derived from MODIS data were idenfied for the territory of beech forest stands in Slovakia in the period 2000 – 2010. Between the date of onset of the individual phenological events and altitude there is moderate non-linear relationship. The onset of spring phenophases delays with increasing altitude, the onset of autumn phenophases decreases with altitude, except of the sites with low altitude where the dry conditions at the end of vegetation season probably cause premature yellowing. The length of the growing season of European beech decreases with altitude.

Regional phenology model for European beech (Fagus sylvatica L.) has been validated on an extensive range of phenological observations. The time series of phenological observation of regional phenological observation sites of Slovak Hydrometeorological Institute for years from 2000 to 2009 and permanent monitoring plots of National Forest Centre for 2002 – 2009 was used to validate the timing of five main spring and autumn phenological events.

The most accurately were derived the phenological events the first leaves, full leafing and the beginning of colouring of leaves. The resulting duration of full foliage was derived with an average error of ± 4.2 days (r = 0.84). Date of onset of phenophases bud break and full colouring of leaves, determining the duration of the entire growing season, were derived with a systematic negative (budbreak), respectively. positive error (full colouring) which increases with increasing altitude. It resulted in an overestimate of the duration of the growing season by an average of 26 days. Modeling is a useful tool that provides us information about (not only) forest ecosystems with high temporal and spatial resolution, but it can be used to predict changes in the phenology of forest tree species due to climate change. Validation using ground-based measurements, respectively. observation allows the model results to be correctly interpreted.

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Summary

V príspevku popisujeme metódy a výsledky validácie regionálneho fenologického modelu odvodeného z NDVI (Normalized Difference Vegetation Index, normalizovaný vegetačný index) zo satelitných snímok MODIS (Moderate Resolution Imaging Spectroradiometer) pre drevinu buk lesný (*Fagus sylvatica* L.). Na validáciu dňa nástupu piatich hlavných jarných a jesenných fenologických udalostí bol použitý rad pozorovaní regionálnych fenologických staníc SHMÚ (Slovenský hydrometeorologický ústav) z rokov 2000 - 2009 a rad fenologických pozorovaní na trvalých monitorovacích plochách NLC (Národné lesnícke centrum) z rokov 2002 - 2009.

Najpresnejšie boli odvodené dni nástupu fenofáz začiatok zalisťovania, všeobecné zalisťovanie a začiatok žltnutia. Z nich vyplývajúca dĺžka trvania plného olistenia, rozhodujúca pre celkovú produkciu, bola odvodená s priemernou chybou ±4,2 dni (r=0,84). Dni nástupu fenofáz rašenie pupeňov a všeobecné žltnutie listov, určujúce dĺžku trvania celého vegetačného obdobia, boli odvodené so systematickou zápornou (rašenie pupeňov), resp. kladnou chybou (všeobecné žltnutie listov), ktorá sa zvyšovala s nadmorskou výškou, čím došlo k nadhodnoteniu dĺžky trvania vegetačnej sezóny v priemere až o 26 dní. Možné príčiny zistených rozdielov v čase nástupu jednotlivých fenofáz a dĺžke ich trvania sú diskutované v príspevku.

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