

Spring phenology of oak stands in the Western Carpathians: validation of satellite metrics from MODIS using ground-based observations

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Abstract

The study focuses on the validation of the leaf unfolding (LU) onset of oak stands in the Western Carpathians in 2000–2021 derived from MODIS satellite data. LU onset was derived from the annual trajectories of the Normalised difference vegetation index (NDVI) fitted with a double sigmoid logistic function. The satellite metric Growing speed day (GSD) corresponding to the LU onset is represented by the first derivative of the sigmoid function. Ground-based observations from 22 phenological stations of the Slovak Hydrometeorological Institute (SHMI) were used to validate the date of GSD. The results showed a good agreement between the medians of ground- and satellite-based LU onset dates. In addition to the median, the LU onset at the 5th and 95th percentiles were compared. For both percentiles, we found differences in the onset from MODIS and SHMI. The 5th percentile of the LU onset derived from MODIS was determined later than the one from SHMI data. With the 95th percentile, it was the opposite. As a result, the range determining the duration of LU onset from MODIS was significantly shorter than from SHMI observations. The trend analyses over the period 2000–2021 revealed a shift to the earlier onset of LU $\sim 0.33 \text{ day} \cdot \text{year}^{-1}$ ($p = 0.13$) from satellite and $\sim 0.32 \text{ day} \cdot \text{year}^{-1}$ from ground-based observations ($p = 0.08$). The validated LU onset and trends using the median allow analysing of the oak stands' response to changing environmental conditions. However, the differences at the 5th and 95th percentiles, i.e. at the beginning and the end of the LU onset duration, remained unexplained.

Key words: MOD09; MYD09; NDVI; leaf unfolding; validation

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1. Introduction

Forest phenology is a traditional scientific discipline that examines the time course of important, periodically recurring life manifestations of forest trees, the so-called phenological phases. The onset of phenophases depends mainly on the weather (Štefančík 1995) and is influenced by the changing climate. Therefore, the phenophases' onsets are considered indicators of climate change impacts on forests (Richardson et al. 2013; Gray & Ewers 2021). A new dimension to study forest ecosystem responses to changing environmental conditions at global and macro-regional levels was provided by the satellite-based phenology using the Advanced Very High-Resolution Radiometer (AVHRR) (Stöckli & Vidale 2004; Piao et al. 2006; Heumann et al. 2007). The main benefit compared to sampling methods based on ground-based observations lies in the possibility of quasi-continuous (in day intervals) and large-scale monitoring

of the course of phenological events. The AVHRR's resolution of 8 km was the main limiting factor in their use.

In Slovakia, satellite phenology has gained an importance following the launch of the Terra and Aqua satellites (2000, 2002, NASA Earth Observation System Satellites) with the Moderate Resolution Imaging Spectroradiometer (MODIS). For the red and infrared bands, the pixel size of $250 \times 250 \text{ m}$ is already sufficiently detailed to identify and select a sufficient number of homogeneous pixels with one type of landscape cover for analyses, even in the fragmented area of the Slovak forests (Bucha et al. 2011). Currently, a consistent database was created from 2000 to 2021. It is based on MODIS products MOD09GQ and MOD09GA derived from the Terra satellite and MYD09GQ and MYD09GA from the Aqua satellite. The products contain a quality layer that allows eliminating pixels with reflectivity affected by clouds, cloud shadows or high aerosol content. Several papers demonstrated the suitability of using the Normalized Differen-

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tial Vegetation Index (NDVI) derived from satellite data to monitor phenophases in forests (Zhang et al. 2003; Beck et al. 2006; Soudami et al. 2008).

Modelling methods are used to derive satellite-based phenological metrics. Under modelling, we understand a mathematical expression of the course of NDVI development during the year and determine the onset of major phenological events. Berra & Gaulton (2021) report that the logistic function (Zhang et al. 2003) and its modifications (Fisher et al. 2006; Fisher & Mustard 2007) is the most commonly used function in deriving vegetation phenology at local and regional levels. In Slovakia, the double logistic function was used for modelling (Bucha & Koreň 2017; Lukasová et al. 2014, 2019; Barka et al. 2019; Tholt 2021) through the PhenoProfile software application (© Milan Koreň). The main advantage of this application is the full user control of modelling parameters and the possibility to refine the modelling procedures. Its main functionalities were described by Bucha & Koreň (2014).

The rapid expansion in remote sensing and ground-based phenology data acquisition has supported significant advances in plant phenological research, as shown in the recent review (Piao et al. 2019). However, some research results point at methodological risks in deriving and interpreting phenological models based on satellite data from various sensors (Norris et al. 2020; Younes et al. 2021). Therefore, the validation of derived regional products still appears to be very topical and necessary.

Data from terrestrial measurements are used for validation and parameterization of remote sensing outputs (Hmimina et al. 2013). The onset of individual phenophases derived from MODIS for beech stands in Slovakia was validated by Pavlendová et al. (2014) and Lukasová (2019) by comparison them with observations from the network of phenological stations of the Slovak Hydrometeorological Institute (SHMI). In addition to SHMI data, they also used their own observations. A validation for oak stands has not been performed, yet.

Therefore, our first goal is to validate a regional phenological model derived from NDVI from MODIS satellite images for oak stands. The observations from the SHMI regional phenological stations for the period 2000–2021 were used to validate the day of the onset of the leaf unfolding (LU) spring phenophase. SHMI observations were used to verify the hypothesis that the local extreme of the first derivative of Fisher's sigmoidal function (Fisher & Mustard 2007) is related to the leaf unfolding onset. Based on the knowledge of the Fisher's function course and its validation in beech stands (Pavlendová et al. 2014), we assume that the LU phenophase of oak will correspond to the GSD (Growth Speed Day) satellite metric. The LU onset phenophase was chosen because it is used as the start of the growing season. In contrast to published studies, we validate the onset of LU derived from MODIS over the entire duration of the phenophase using 5-percentile, median (50-percentile) and 95-percentile. The validation of the 5th and 95th

percentiles is important for understanding the response of oak stands in the boundary conditions of their occurrence.

The second goal of the work is to derive and compare temporal trends of the LU onset from ground surveys and satellite data. We assume that the trends derived from both data sets will be identical. Due to the continuity of data acquisition with MODIS, after the validation it will be possible to analyse LU changes more accurately and use the new knowledge in proposing climate change adaptation measures in forests.

2. Material and methods

2.1. Study area

We carried out the research in the forest stands of Slovakia with a dominant presence of pedunculate oak (*Quercus robur* L.) and/or sessile oak (*Quercus petraea* Liebl.) (Fig. 1). These are economically important trees with a total share of 10.4% of forest area (Moravčík et al. 2021). The species are not differentiated and are analysed together as one genus in the study.

Geographically, most of the territory belongs to the province of the Western Carpathians, while a part of the eastern Slovakia roughly from 21°15' longitude belongs to the province of the Eastern Carpathians (Kočík & Ivanič 2011). The occurrence of assessed oak stands is concentrated in the 1st to 3rd forest vegetation zones from the 8-level scale (Zlatník 1976). It is an area with an average annual temperature above 5.5 °C, annual precipitation totals up to 800 mm and a growing season of 150 to 180 days. The dominant soil on which oak stands occur are cambisols, followed by leptosols, luvisols and planosols (Miklós 2002).

2.2. Oak stands selection

When selecting oak stands, we used the tree species map of Slovakia from Landsat (Bucha 1999) with a resolution resampled to 250 m in a combination with the current database of the Forestry Information System (FIS). The database contains data at the compartment level (NFC Zvolen – <https://gis.nlc.sk.org/lgis/>). Data from FIS was used to calculate the proportion of oak in 250 m pixels. We excluded marginal pixels from the tree species map. The reason is that these pixels in the MOD09 products may be spectrally contaminated with other land cover categories (Townshend et al. 2000) and thus distort the derived NDVI values. We also excluded pixels where the oak proportion was less than 70%. Thus, created masks of homogeneous oak stands contained 981 pixels. Of these, we selected 413 pixels by stratified random sampling, on which the LU onset was analysed (Fig. 1). The number of points ensured the representatives of the sample. At the same time, the iterative calculation of 6 parameters

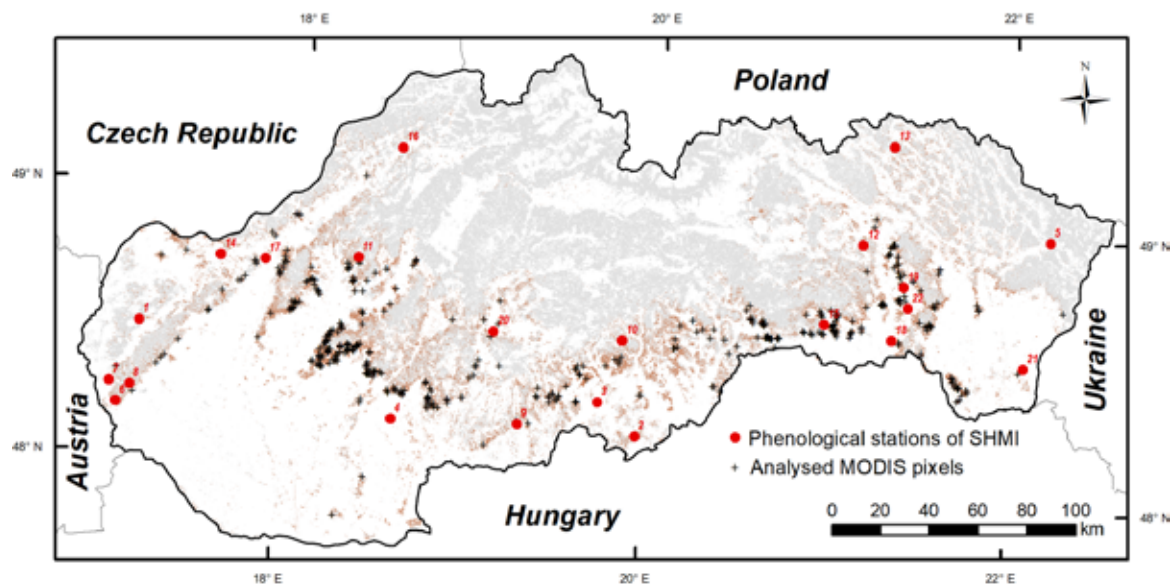


Fig. 1. Forests with a predominant occurrence of oak (brown colour), the spatial distribution of SHMI phenological stations (red circles) and analysed pixels from MODIS with the occurrence of oak $\geq 70\%$ (black crosses). The forests are shown in grey. The numbering of the phenological stations is in accordance with Table 2.

of Fisher's function modelling the NDVI profile during the year was manageable in about 6 hours on a PC with a six-core processor. The altitudinal distribution of the analysed oak pixels is shown in Fig. 2a. Fig. 2b depicts the altitudinal distribution of SHMI stations.

2.3. Modelling of the annual NDVI course

The solution was based on MODIS images, specifically on products MOD/MYD09GQ and MOD/MYD09GA collections 5 and 6. The products represent the spectral reflectance on the earth's surface, i.e. the effect of absorption and scattering of radiation in the atmosphere was eliminated. From the MOD09GQ and MYD09GQ products, we derived the NDVI using the red and infrared bands with a pixel resolution of 250×250 according to

the relationship:

$$NDVI = \left(\frac{NIR_{841-876 \text{ nm}} - Red_{620-670 \text{ nm}}}{NIR_{841-876 \text{ nm}} + Red_{620-670 \text{ nm}}} \right) \quad [1]$$

The layer of quality was taken from the MOD/MYD09GA products. Using the layer, we excluded pixels affected by cloud cover, cloud shadows and high aerosol content from the analyses. By overlaying the NDVI layer adjusted in this way with a layer of selected oak stands, a database suitable for modelling oak phenology was created. The procedure for choosing and pre-processing MODIS images and deriving NDVI is described in detail in Bucha & Koreň (2014 and 2017).

The subject of the analysis was the NDVI time series from March to July and the years 2000 to 2021. The annual development of NDVI was modelled by a double

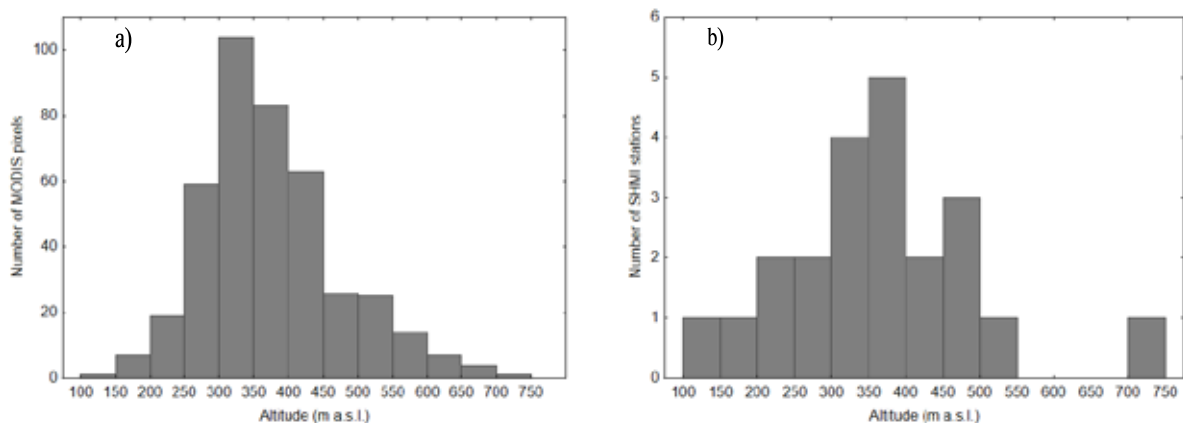


Fig. 2. a) Frequency histogram of oak stands (with oak share of 70% and more) along the altitudinal range. b) Frequency histogram of altitude distribution of SHMI stations. X-axis: altitude (m a.s.l.). Y-axis: a) number of pixels (MODIS); b) number of SHMI stations.

logistic function (Fisher & Mustard 2007):

$$v(t) = v_{\min} + v_{\text{amp}} \left(\frac{1}{1 + e^{m_1 - n_1 t}} - \frac{1}{1 + e^{m_2 - n_2 t}} \right) \quad [2]$$

where $v(t)$ is NDVI observed at time t ; v_{\min} and v_{amp} are parameters corresponding to the minimum value of the NDVI and its amplitude; m_1 and n_1 parameters control the shape and slope of the curve of the ascending (spring) phase, and m_2 and n_2 parameters control the descending (autumn) phase.

The advantage of using this type of the sigmoid function is that it is differentiable. The extremes of the first and second derivatives of equation 2 were used to derivate satellite metrics and corresponding phenological events. The connection of spring phenophases from ground observations and satellite metrics is shown in Table 1 based on Pavlendová et al. (2014).

Table 1. Satellite-based phenological metrics and corresponding vegetative phenophases by Pavlendová et al. (2014).

Satellite metrics	The description of satellite phenological metrics derived from [2] – Corresponding vegetation phenophases
GAD	Maximum of the second derivative in a spring phase ~ Bud break onset
GSD	Extreme of the first derivative in a spring phase (spring inflection point) ~ Leaf unfolding (LU) onset
GDD	Minimum of the second derivative in a spring phase ~ End of leaf unfolding

GAD – Growing Acceleration Day; GSD – Growing Speed Day; GDD – Growing Deceleration Day; DOY – Day of Year.

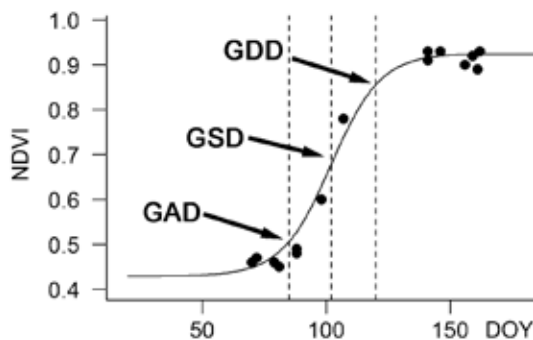


Fig. 3. The course of the NDVI curve in the spring phase. The black dots represent the NDVI in a given pixel on a given DOY.

In this work, we analyse only the phenophase of leaf unfolding. LU onset was evaluated according to the scale of the manual for phenological observations for the pan-European monitoring system (Preuhsler 1999) and according to the scale developed by SHMI (Braslavská & Kamenský 1996). The LU onset is considered the DOY when the first light green leaves, smaller than in adulthood, appeared on at least half of the individuals of the given observed group.

The GSD satellite metric corresponds to the LU onset phenophase. GSD is defined as the date when the sigmoid reaches its half-maximum value or peak of the first derivative of the equation [2]. Fisher & Mustard (2007) state that the half-maximum represents the date when

most leaves are likely to emerge and that deciduous forests with different crown canopies or even small amounts of conifers can be compared at the date of onset. The GSD date was calculated for each of the 413 analysed pixels for each year from 2000–2021.

2.4. Data validation and statistical evaluation

We used ground-based phenological observations to validate and reveal possible errors in modelling LU onset from MODIS. From the SHMI network, we used 22 forest phenological stations focused on oak evaluation (Fig. 1; Table 2), where more than 95% of the data on the LU onset were available in individual years from 2000–2021. Observations were made individually using a telescope. 10 pre-dominant or dominant trees were evaluated at each plot. In the next text, where it is necessary to distinguish the LU onset between ground and satellite observations, we use the abbreviations LU_SHMI and LU_MODIS.

Table 2. Basic characteristics of selected SHMI forest phenological stations.

Station number – see Fig. 1.	Station name	Latitude	Longitude	Altitude [m a.s.l.]
1	Riadok	48° 30'	17° 10'	183
2	Hajnáčka	48° 13'	19° 57'	250
3	Lučenec	48° 20'	19° 41'	250
4	Levice	48° 13'	18° 37'	280
5	Stakčín - CHOTINA	49° 00'	22° 13'	300
6	Železná studienka	48° 10'	17° 07'	320
7	Stupava	48° 16'	17° 02'	320
8	Hvezdáreň	48° 22'	17° 17'	350
9	Čebovská Bukovina	48° 14'	19° 18'	360
10	Kokava nad Rimavicou	48° 34'	19° 51'	370
11	Kšinná	48° 48'	18° 21'	374
12	Prešov-Cemjata	48° 58'	21° 10'	375
13	Zborov	49° 22'	21° 18'	400
14	Myjava	48° 46'	17° 35'	450
15	Jasov Lesy-Premonstr.	48° 40'	20° 58'	450
16	Bytča-Starovec	49° 14'	18° 33'	460
17	Nové Mesto nad Váhom	48° 46'	17° 50'	500
18	Ždaňa	48° 34'	18° 45'	500
19	Kecеровce	48° 49'	21° 24'	550
20	Zvolen	48° 34'	19° 10'	718
21	LS Veľké Kapušany	48° 32'	22° 05'	108
22	LS Svinica	48° 44'	21° 28'	350

The SHMI stations are evenly distributed across Slovakia so that the highest possible number of tree species can be observed simultaneously in each station (Fig. 1). Therefore, it was impossible to match stations with analysed oak pixels from MODIS. For this reason, we used the two-sample Kolmogorov-Smirnov test to test the agreement of the altitude distribution of two sample sets, i.e. 413 pixels from MODIS and 22 SHMI stations. The hypothesis H0: The two samples follow the same altitudinal distribution was tested against H1: The altitudinal distributions of the two samples are different. The reason for testing the equality of altitudinal distributions is the strong dependence of LU onset to the altitude. Any differences in sample sets would bias the comparison of differences between LU_SHMI and LU_MODIS, as well

as validation of LU onset modelling from MODIS data in individual years 2000–2021.

For the nationwide evaluation of the LU onset (LU_SHMI and LU_MODIS) of oak stands, we calculated the median value in individual years of the period 2000–2021. We expressed the intra-annual variability with the 5th and 95th percentiles. These represent the LU onset day values below which 5 (95) % of the distribution lies. This means that the 5th percentile represents the day of LU onset at lower altitudes or in southern areas. The 95th percentile represents the day of LU onset at higher altitudes or in northern regions of oak occurrence. We note that the median represents the 50th percentile.

The uncertainty in the LU onset assessment from MODIS was analysed with statistical metrics such as a Coefficient of determination (R^2), Mean bias error (MBE) and Mean absolute error (MAE). The statistical metrics were used to compare the model's performance in deriving the GSD using equation [2] with SHMI observations.

Coefficient of determination (R^2):

$$R^2 = \frac{\left[\frac{\sum (Y_f - \bar{Y}_f)(Y_m - \bar{Y}_m)}{\sqrt{\sum (Y_f - \bar{Y}_f)^2 \sum (Y_m - \bar{Y}_m)^2}} \right]^2}{[3]}$$

Mean bias error (MBE):

$$MBE = \frac{\sum (Y_m - Y_f)}{N} [4]$$

Mean absolute error (MAE):

$$MAE = \frac{\sum |Y_m - Y_f|}{N} [5]$$

where Y_f = ground-based value (LU onset from SHMI), Y_m = modelled value (LU onset from MODIS), \bar{Y}_f = average of Y_f values, \bar{Y}_m = average of Y_m values, N = number of years in the analysed period 2000–2021.

We used a simple linear correlation and regression analysis to derive temporal trends in LU onset from SHMI and MODIS data. The input was the time series of the median values of the LU onset calculated for individual years of the period 2000–2021. We assessed the significance of the trends by testing the significance of the sample correlation coefficients. Under hypothesis H_0 , the correlation coefficient in the population is equal to 0. It is proven that testing the significance of the correlation coefficient is identical to testing the significance of the regression coefficient (Šmelko 1991). The test characteristic t was used. For $t > t_{\alpha, p}$ the hypothesis H_0 is rejected at α % level of significance, and with $P = 1 - \alpha$ % confidence it is considered that both the correlation and the regression sample coefficients are different from 0.

We verified whether the trends derived from MODIS and SHMI were significantly different by testing the hypothesis about the equality of the two regression coefficients.

3. Results

3.1. Comparison of altitudinal distribution of SHMI and MODIS data sets

The results of the Kolmogorov-Smirnov test, with which we tested the equality of the altitudinal distribution of the two sample sets, are presented in Table 3. The overlap of the cumulative distribution functions of SHMI and MODIS samples documents the equality of their altitudinal range in Fig. 4. Therefore, we consider that the samples follow the same altitudinal distribution and are suitable for:

- comparing the onset of LU from ground-based and MODIS observations,
- identification of modelling inaccuracies in individual years 2000–2021,
- validation of LU onset from MODIS.

Table 3. Two-sample Kolmogorov-Smirnov test for comparing the equality of the altitudinal distributions of ground-based and MODIS phenological plots.

Source	Number of plots	p-value	Significance level – alpha	Interpretation
SHMI	22	0.883	0.05	As the computed p-value > alpha, one cannot reject the null hypothesis H_0 : The two samples follow the same distribution.
MODIS	413			

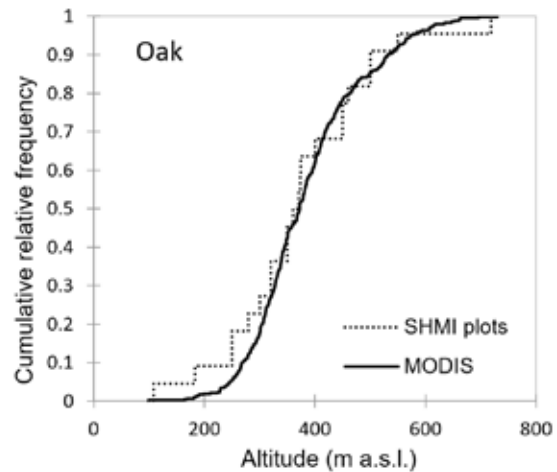


Fig. 4. Comparison of the equality of the cumulative altitudinal distribution of ground-based phenological plots of the SHMI stations and MODIS pixels.

3.2. Validation of LU onset from MODIS using ground-based observations

Input data on the LU onset from ground-based SHMI observations (LU_SHMI) and MODIS (LU_MODIS) are presented in Table 4. The course of both onsets is graphically compared in Fig. 5a–c, where the medians, 5th and 95th percentiles express the day of LU onset for individual years of the period 2000–2021.

Table 4. Median, 5th and 95th percentiles of leaf unfolding from MODIS (413 pixels) and from phenological observations in the SHMI network (22 stations).

Year	LU_MODIS median	5th percentile	95th percentile	LU_SHMI median	5th percentile	95th percentile
2000	111	109	113	114	105	119
2001	119	116	122	117	101	125
2002	119	111	121	114	104	125
2003	117	115	121	118	111	125
2004	116	112	122	119	110	128
2005	115	110	119	122	110	134
2006	115	112	121	120	110	129
2007	105	101	111	109	99.2	120
2008	115	110	122	115	103	126
2009	104	102	111	108	103	119
2010	115	111	119	118	105	125
2011	108	105	113	111	105	120
2012	115	110	119	116	102	125
2013	117	115	121	117	110	123
2014	96	91	102	103	89	119
2015	111	108	117	113	90.3	123
2016	105	102	109	108	90.5	121
2017	106	97	119	107	93.1	123
2018	107	105	108	108	96.3	117
2019	106	102	114	110	93.1	119
2020	109	106	116	110	97.1	121
2021	124	119	129	123	105	135
Average	111.59	107.68	116.77	113.64	101.48	123.68

Table 5 shows the differences (Δ) in days between the LU onset from ground observations and MODIS using MBE and MAE statistics derived according to relations [4] and [5]. We found the smallest differences in the LU onsets between the medians and the largest for the 95th percentile. The difference between the 5th percentiles was also substantial. The median MBE of -2.05 days indicates an earlier determination of LU onset from MODIS compared to ground observations. Similarly, MBE of -6.91 days for the 95th percentile represents an earlier determination of LU onset from MODIS. Conversely, the MBE of 6.20 days for the 5th percentile represents the later onset from MODIS versus SHMI.

Table 5. Mean bias error (MBE) and Mean absolute error (MAE) in days between SHMI and MODIS leaf unfolding onset for median, 5th percentile and 95th percentile.

	ΔLU_{median}	$\Delta LU_{5th_percentile}$	$\Delta LU_{95th_percentile}$
MBE	-2.05	6.20	-6.91
MAE	2.77	6.29	6.91

A close relationship between the median LU onset values from MODIS and SHMU is evident from the course of DOY during the entire observed period (Fig. 5a). It confirms the suitability of the GSD metric for determining LU onset from MODIS. At the same time, it was possible to identify the years with greater differences between satellite and ground-based DOYs that may indicate possible errors in determined values that need to be checked. These are mainly the years 2002, 2005, 2006 and 2014. For these years, we re-derived the LU_MODIS onset day (GSD metric) by changing the modelling parameters. We expanded the parameter ranges of function [2] and doubled the subspaces within which the iteration process took place. The calculation extended to more than three days, but in no case did the difference exceeds 0.2 days compared to the estimate

with the original parameters. Therefore we consider the LU_MODIS onset DOY as confirmed.

The regression dependence between the onset of LU_SHMI and LU_MODIS is expressed in Figures 5d–f. The highest correlation coefficient and the concentration of the points around the line $y = x$ was observed for the median LU values (Fig. 5d).

The calculated differences between the 95th and 5th percentiles, which determine the duration of the LU onset phase, are shown in Fig. 6a for the entire monitored period 2000–2021. The graph shows that the duration of LU onset from MODIS was systematically underestimated compared to ground observations of SHMI. The significant difference results from the two already described opposite tendencies of LU determination at the 5th and 95th percentiles.

3.3. Temporal trend of leaf unfolding onset

Median values of the day of LU onset, intra-annual variability expressed by the 5th and 95th percentiles for the individual years of the period 2000–2021 and the calculated linear trends of the LU onset are shown in Fig. 7a and 7b for SHMI and MODIS selection of oak stands, respectively.

Fig. 7a and 7b show considerable intra- and inter-annual variability of DOY of leaf unfolding onset. In the Carpathian conditions, the intra-annual variability is mainly conditioned by the altitude and the related air temperature. The inter-annual variability is determined by the spring weather. Both SHMI and MODIS observations show a tendency towards an earlier LU onset over the period 2000 to 2021. The regression coefficient determines the magnitude of the change per year. For ground-based SHMI observations, this change was $-0.32 \text{ days} \cdot \text{year}^{-1}$ ($p = 0.08$) and for MODIS it was

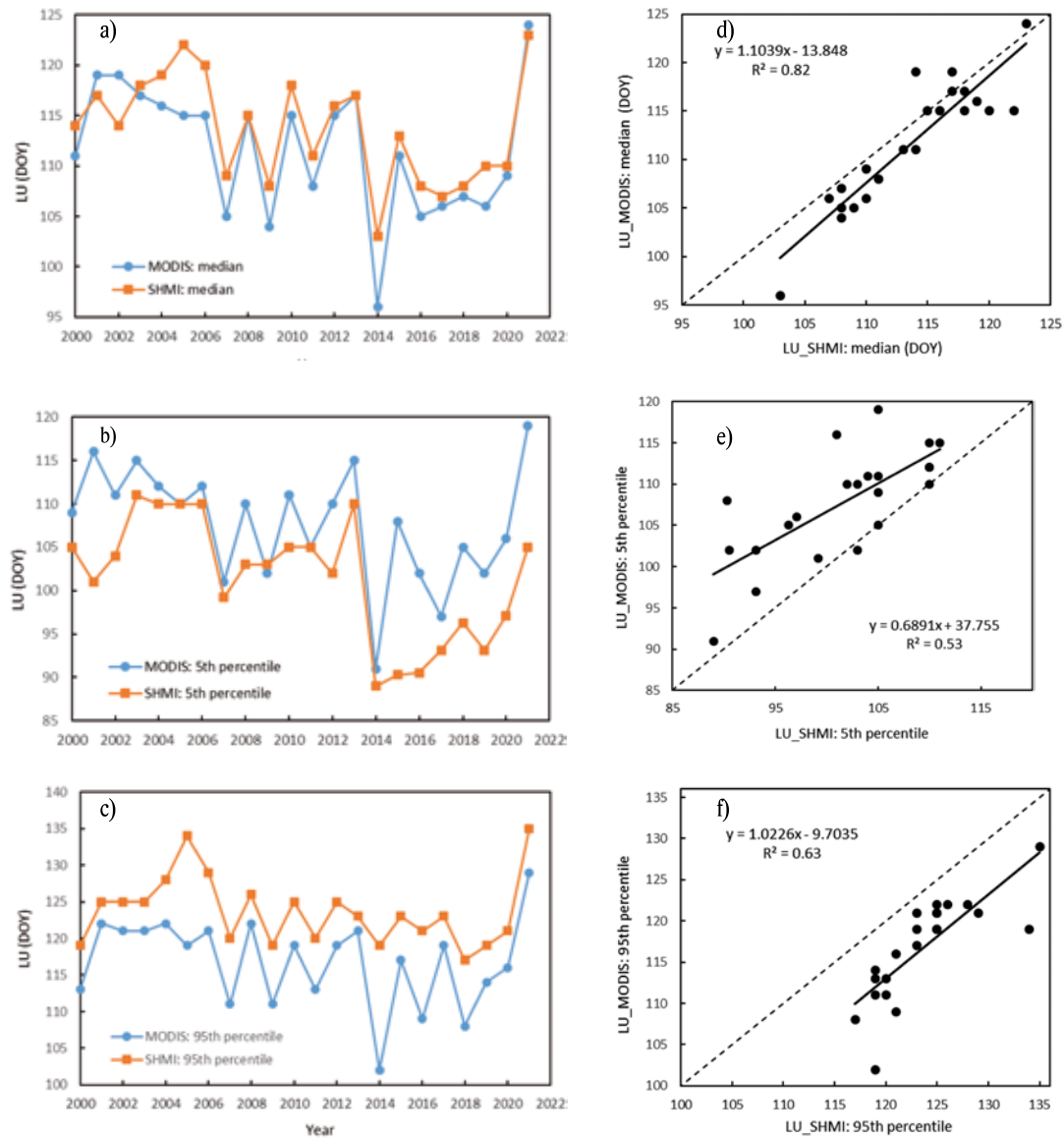


Fig. 5. Left: Comparison of the leaf unfolding onset from SHMI and MODIS observations for the period 2000–2021: a) median, b) 5th percentile, c) 95th percentile. X-axis: year; Y-axis: Day of the year (DOY). Right: Dependence between the leaf unfolding onset from SHMI and MODIS observations for d) median, e) 5th percentile, f) 95th percentile. X- and Y-axes: Day of the year (DOY). The dashed line corresponds to the line $y = x$.

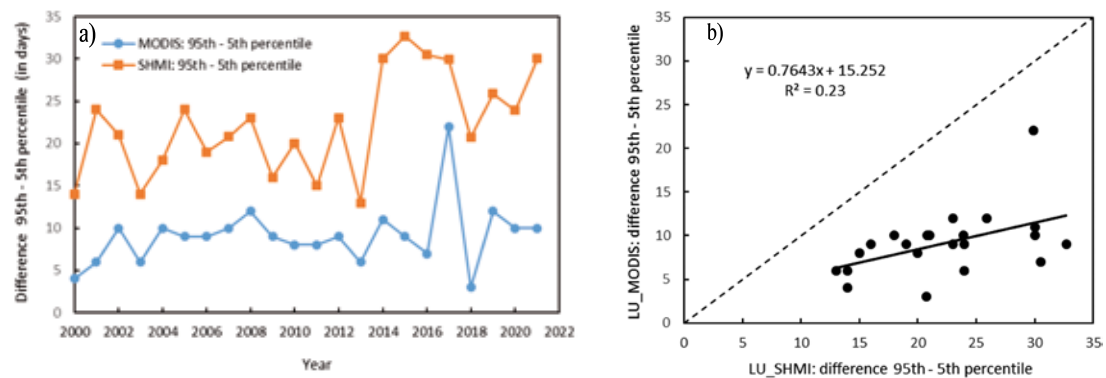


Fig. 6. Course (a) and dependence (b) between the duration of the LU onset on 22 SHMI phenological stations and 413 MODIS pixels. Duration is expressed in days and is calculated as the difference between the 95th and 5th percentiles for each year of the period 2000–2021.

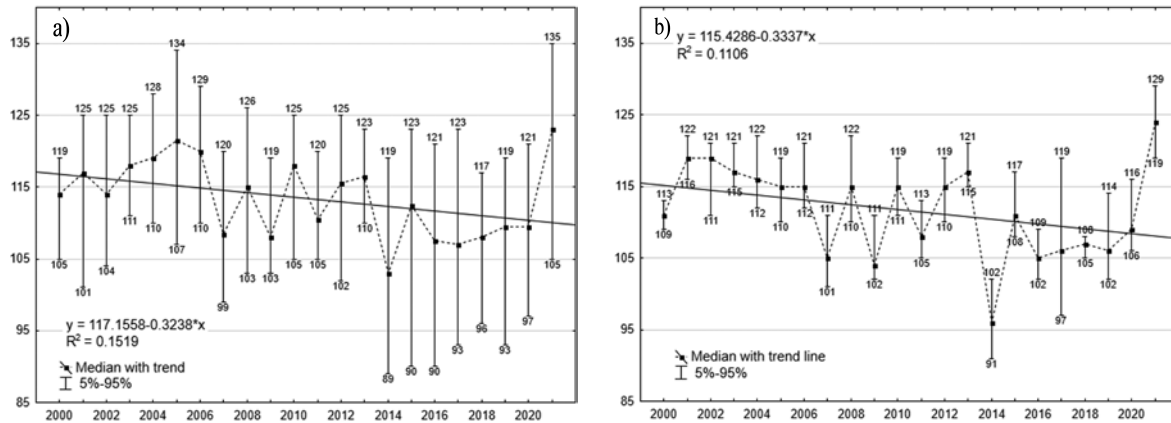


Fig. 7. Leaf unfolding onset day (median), duration (5th and 95th percentile) and onset trends of oak stands for the period 2000–2021 according to a) SHMI observations and b) MODIS. X-axis: year; Y-axis: Day of the year (DOY).

$-0.33 \text{ days} \cdot \text{year}^{-1}$ ($p = 0.13$). The test of the hypothesis about the equality of regression coefficients proved that the slope of both regression lines was identical ($p < 0.001$).

4. Discussion

4.1. Notes on phenological modelling and validation of results

The day of the leaf unfolding onset was derived from NDVI annual trajectories fitted with the double logistic function according to formula [2]. Only the spring period from about 70 to 200 DOY was analysed. The parameters m_2 , n_2 of equation [2] are decisive for autumn phenophases and do not affect the calculation of spring parameters in eq. [2]. Therefore, the NDVI images from DOY above 200 were not included in the modelling.

The LU onset determined from 413 MODIS pixels and 22 SHMI phenological stations and expressed by the median had a comparable course during the monitored period 2000–2021 (Fig. 5a). We checked the four more substantial differences in 2002, 2005 and 2006 and 2014 by recalculating the DOY of LU onset from MODIS. The refined DOY derivation did not differ substantially from the original one. We did not find an exact explanation for the identified differences, as significant differences did not occur in other years. It is also not possible to rule out the error of the ground-based phenological observations due to the subjectivity of the observers.

4.2. Inter-annual variability of the leaf unfolding onset

The days of LU onset expressed by the median during 2000–2021 naturally varied depending on the spring weather. Annual median values ranged from 96 to 124 DOY for MODIS and from 103 to 123 DOY for SHMI (Fig. 5a). The mean value for the period 2000–2021 was

111.6 DOY in MODIS and 113.6 DOY in SHMI observations.

In both data sets, we recorded the earliest onset of LU in 2014, when the median DOY for Slovakia was 96 (MODIS), or 103 (SHMI). The year 2014 was historically the first year in Slovakia when the cumulative value of the average daily air temperature exceeded all previous observations since 1951 (Bochníček 2014 – available online).

In 2021, we observed the atypical late onset of LU DOY equal to 124 DOY (MODIS) and 123 DOY (SHMI). According to the SHMI meteorological report, the temperature in March 2021 was normal, but the temperature in April was below average in the entire territory of Slovakia and the weather was unstable and cold. This type of weather had a contrary character compared to the above average air temperatures in April in the previous decade. It was related to atypical circulation conditions in the northern hemisphere resulting from the global climate change (SHMÚ, 2021).

4.3. Intra-annual variability of leaf unfolding onset

The intra-annual variability of the LU onset is mainly conditioned by climatic conditions resulting from the altitude and the current development of the weather in a given year. The air temperature plays a decisive role (Škvareninová 2008). Gafenco et al. (2022) found a longitudinal shift in the budburst of *Quercus petraea* in Romania. Besides, the variation in leaf flush timing involves some ecological trade-offs in temperate regions. For example, the phenological form of pedunculate oak (*Quercus robur* var. *praecox*) in Eastern Poland flushes early in the season to avoid summer droughts but consequently suffers from later spring frost and insect herbivory, whereas the other oak form (*Quercus robur* var. *tardiflora*) flushes up to five weeks later in the season, avoiding insect herbivory but suffering from summer

droughts (Wesołowski & Rowiński 2008; Puchałka et al. 2017).

We expressed the range of oak stands LU onset in individual years using the 5th and 95th percentiles (Fig. 5b and 5c). For both percentiles, we found differences in determining the LU onset between MODIS and SHMI. Moreover, the nature of the difference was contradictory. The 5th percentile of the onset determined from MODIS occurred later than from ground observations. For the 95th percentile, we observed the opposite. When determining the duration of the leaf unfolding onset in Slovakia from MODIS, the phenophase was the shortest in 2000 and 2018, lasting only 5 or 4 days. The longest phenophase duration was found in 2017, equal to 23 days. In other years, it varied from 7 to 13 days. According to ground-based phenological observations of SHMI, the shortest phenophase duration was in 2013, 2000 and 2003, namely 14 and 15 days. The most extended duration of the phenophase was found in 2015, namely 33 days. In other years, it varied from 16 to 31 days.

Due to the opposite nature of determining the 5th and 95th percentiles of LU onset from MODIS compared to SHMI, the resulting range of the phenophase duration was even more different than for the individual percentiles. This was manifested by a substantially shorter range of the LU onset in MODIS than in SHMI observations. The average duration of the phenophase from MODIS for the entire monitored period was 10.1 days, while according to SHMI it was up to 23.2 days.

A partial explanation for the significant difference is the uneven geographical distribution of SHMI stations and pixels from MODIS. From Fig. 1 we can see that some SHMI stations are located further south (stations no. 2, 4, 6–9, 21) but also further north (stations no. 5, 13, 16) than most MODIS pixels. Considering the south-north and partly the west-east dependence of the onset of spring phenophases (with increasing latitude and continentality, the phenophase is delayed) and the smaller number of SHMI stations, it cannot be ruled out that the mentioned factors affected the comparability of SHMI and MODIS data despite the agreement of their altitudinal distribution. For example, Stakčín and Zborov stations, which are the most northern and at the same time the most eastern, but also Bytča-Starovec, which is located in the northwest of the country, regularly had the late LU onset. This affects the 95th percentile of LU onset. The southerly located SHMI stations, Hvezdárň in the west, Hajnáčka in the middle and Veľké Kapušany in eastern Slovakia, usually had the earliest onsets of the phenophase. This was manifested in the 5th percentile towards the earlier LU onset compared to MODIS. Barka et al. (2019) quantified a delay in LU onset towards the North by 1.05 days per 100 km from MODIS data for beech forests in the Pannonian-Carpathian macro-region. The longitudinal delay was observed as well but was not significant. The LU onset shift due to latitude/

longitude has not yet been quantified in the oak forests.

Considering the mask with the oak share of at least 70%, it is not possible to exclude the influence of other tree species occurring in a given pixel on the LU onset. The tree species with the highest representation in Slovakia could have the most significant impact: beech at the 95th percentile, hornbeam and Turkey oak, especially at the 5th percentile due to their altitudinal occurrence. Schieber et al. (2009) showed an earlier beech and hornbeam LU onset of up to 6 days (average for 1995–2007) compared to Sessile oak in central Slovakia. On the contrary, a later LU onset is reported in the case of Turkey oak. When analysing LU onset with an 85% oak mask (136 pixels), we found no shift for the 5th percentile compared to the 70% mask. For the 95th percentile, there was a 1-day shift to a later LU onset and thus a prolongation of the phenophase.

Both effects (a shift due to the earlier LU onset of beech in analysed pixels and possible latitudinal shift) could extend the average 10.1 days-long duration of the LU onset, found in our work, by 2–2.5 days. Despite this, most of the differences remain unexplained.

4.4. Statistics to determine the leaf unfolding onset

From the analysis above of the intra- and inter-annual variability of the LU onset and from the regression dependence between LU_MODIS and LU_SHMI expressed in Fig. 5d–f, it follows that for determining the onset, it is most appropriate to use the median value.

The coefficient of determination between satellite and ground observations was $R^2 = 0.82$ (Fig. 5d), and the Mean bias error (MBE) was -2.05 days, indicating the earlier detection of the LU onset from MODIS (Table 5). The 5th and 95th percentiles are inappropriate metrics if the presented methodical approach is used. In the case of the 5th percentile ($R^2 = 0.53$, $MBE = 6.20$ days), we revealed a substantial shift to a later onset derived from MODIS compared to SHMI. On the contrary, for the 95th percentile ($R^2 = 0.63$, $MBE = -6.91$ days), there was a substantially earlier determination of the LU onset from MODIS compared to SHMI.

The magnitude of the deviation in the median values of LU onset between satellite and ground assessments (MBE -2.05 days and MAE 2.77 days) confirms our assumption that the GSD satellite metric represents the phenophase LU onset and is a suitable metric for satellite-based observations of the mentioned phenophase. The determination of the LU onset at marginal conditions of oak stand occurrence, expressed by the 5th and 95th percentiles, and the duration of the LU onset were not sufficiently validated. The differences between ground and satellite observations should be the subject of further research.

4.5. Temporal trend of the leaf unfolding onset

The length of the monitored period (2000–2021) is sufficient for a statistically relevant derivation of temporal trends in the LU onset. The statistical evaluation results at the national level showed a tendency towards an earlier LU onset of oak stands. The rate of change derived from ground observations was $-0.32 \text{ days} \cdot \text{year}^{-1}$, and $-0.33 \text{ days} \cdot \text{year}^{-1}$ in MODIS observations (see regression coefficients in Fig. 7a and 7b). Over the entire monitored period of 22 years, this represented a shift of ~ 7 days to an earlier start of leaf unfolding. This result is in line with Škvareninová's (2014) finding based on ground observations in Slovakia from 1988–2013, which showed an earlier LU onset of *Quercus robur* by 7 days ($-0.27 \text{ days} \cdot \text{year}^{-1}$). The values of the regression coefficients (LU_SHMI and LU_MODIS) are almost identical, the difference between them was statistically insignificant. This confirms our assumption that MODIS satellite data and the GSD metric derived from them are suitable for temporal analyses and derivation of trends in the LU onset of oak stands. This finding is important because the shift to an earlier onset of the phenophase is a considered response of woody plants to climate change (Berra & Gaulton 2021). Thus, the use of satellite data makes it possible to reliably analyse the reaction of oak stands even at regional or local levels due to the significantly larger MODIS dataset compared to ground surveys.

5. Conclusion

In the presented study, we validated the accuracy of the satellite-based modelling of the leaf unfolding onset spring phenophase. LU onset of a large homogeneous set of oak stands (413 pixels) from the MODIS was compared with data from 22 ground-based phenological stations in the Slovak part of the Carpathians territory. In the case of satellite data, the LU onset corresponds to the extreme of the first derivative of the double logistic function [2] in its spring phase, represented by the GSD metric. From the verified statistics, median, 5-percentile and 95-percentile, we found the closest relationship between ground-based and satellite determination of LU onset at the median calculated from onset days in individual pixels and SHMI stations. The coefficient of determination was $R^2 = 0.82$ with 2.05 days earlier detection of the LU onset by MODIS. We can therefore consider the LU onset from MODIS expressed by the median as validated and reliable for further analyses.

The temporal analysis of the trend over the period 2000–2021 also confirmed the consistency of determining LU onset using the median values. The statistical test confirmed that the regression coefficients determining the rate of the temporal change derived from SHMI and MODIS data were identical. We found a shift of ~ 7 days

to an earlier onset of LU in 22 years. The differences between ground and satellite observations at the 5th and 95th percentiles, i.e. at the beginning and the end of the duration of the LU onset in Slovakia, were not sufficiently explained.

Based on the achieved results, it will be possible to expand the scope of modelling the spring phenophase leaf unfolding onset using continuous satellite data from MODIS. However, the derivation of more accurate results on the reaction of trees to the manifestations of climate change along the altitudinal gradients requires a clarification of the differences in the LU onset between ground-based and satellite data at the peripheral occurrence of oak stands. Only subsequently it will be possible to apply the acquired knowledge, for example, in the forestry decision-making about changes in the transfer of forest reproductive material between forest seed regions or about changes in the regeneration and target tree species composition in management models applicable in the adaptive forestry.

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