Variability of green-up duration of deciduous broadleaf forests in Central Europe during 2000–2019 based on MODIS NDVI

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Background

Spring leaf unfolding is a spectacular recurring event at the mid- and high latitudes that is associated with deciduous vegetation. Contrary to the timing of the start of season (SOS), considerably less attention was paid to studying **the dynamics of vegetation green-up**, characterized by the leaf unfolding speed or **the duration of spring green-up (GUD)**.

The importance of studying the spring green-up dynamics lies in the fact that the duration of leaf development and timing of the onset of growth jointly determine the annual cycle of vegetation activity including carbon and energy balance, canopy conductance and evapotranspiration.

The aim of our research was to characterize the dynamics of leaf unfolding of deciduous broadleaf forests in the wider Carpathian Basin, located in Central Europe, using satellite remote sensing, for 20 years, the period of 2000-2019.

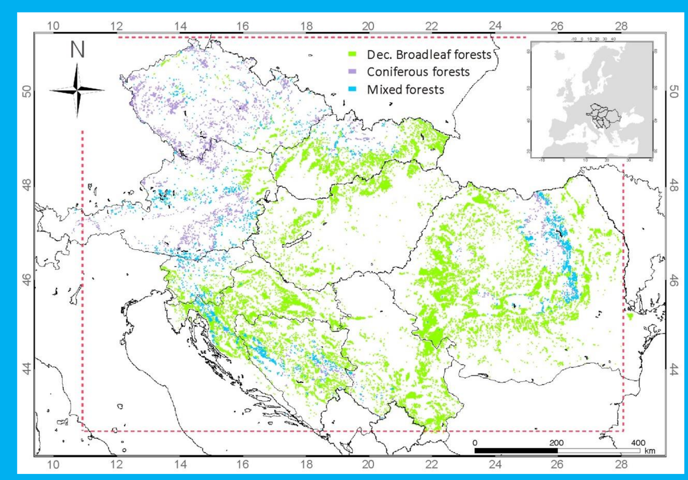

Fig. 1. Map of the study area, showing forests below 1500 m based on the synergistic use of MODIS and CLC2012 land cover

Applied databases

- the **Normalized Difference Vegetation Index (NDVI)** derived from the **MOD09A1 MODIS products during 2000–2019** with 500 × 500 m spatial and „8-day" temporal resolution (*Vermote, 2015*),
- the **IGBP land cover classification** of the MCD12Q1 products (*Sulla-Menashe and Friedl, 2018*),
- the **CORINE 2012** (CLC2012) land cover dataset (*Büttner and Maucha, 2006*),
- the **SRTM elevation** dataset (*Jarvis et al., 2008*),
- and the **FORESEE meteorological database** (*Dobor et al., 2014*), containing daily observation based data based on the E-OBS 17e dataset (*Cornes et al., 2018*).

Steps of the applied methodology at the pixel-level

To calculate the Green-up duration from the remote sensing database (Fig. 2):

1. The pre-processing was performed using the *State* and *Julian day* information included in the datasets, where linear interpolation was applied to fill the data with bad quality flags,
2. The quality checked (preserving only the best quality data) and gap-filled NDVI dataset with „8-day" resolution was resampled into a daily dataset using liner interpolation,
3. $NDVI_{span}$ was defined as: $NDVI_{max}$ - $NDVI_{min}$ during the spring,
4. Start of Season (SOS) was determined as $NDVI_{min} + 0.2 \times NDVI_{span}$,
5. End of Green-up (EOG) was determined as $NDVI_{min} + 0.8 \times NDVI_{span}$,
6. **Green-Up Duration (GUD) was calculated as EOG - SOS.**

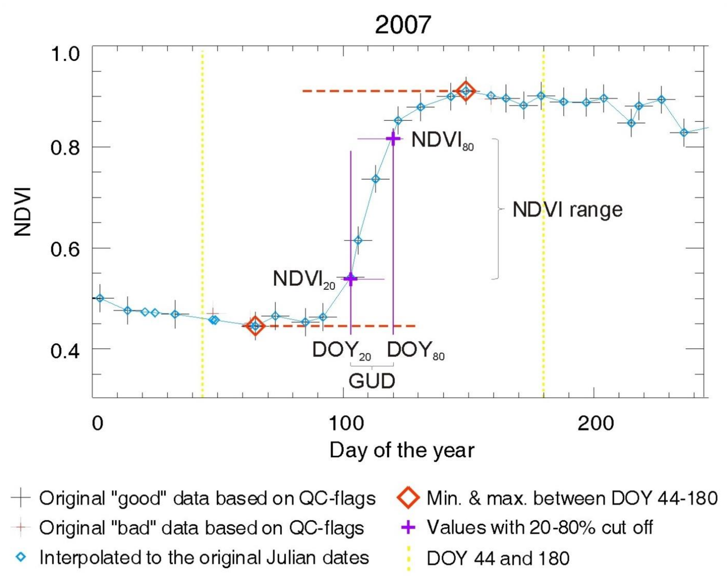

Fig. 2. Overview of the calculation of the green-up duration

To create models:

1. Resampling of the meteorological data to the finer MODIS grid using elevation data, based on Kern et al. (*2016*),
2. Selection of the most influential periods of the meteorological variables affecting the GUD,
3. Construction of diagnostic and prognostic multiple linear models based on:
   (1) meteorological data, (2) site data, and (3) timing of SOS.

R E S U L T S

Climatology of the green-up dynamics during 2000-2019

Green-up dynamics

Based on the relative frequency distribution of the multiannual means:

- **Mean GUD: 23.7 days**
- Mean NDVI range: 0.286
- Mean SOS: DOY 100
- Mean EOG: DOY 123

However, the total width of the distributions are large, and varies between countries.

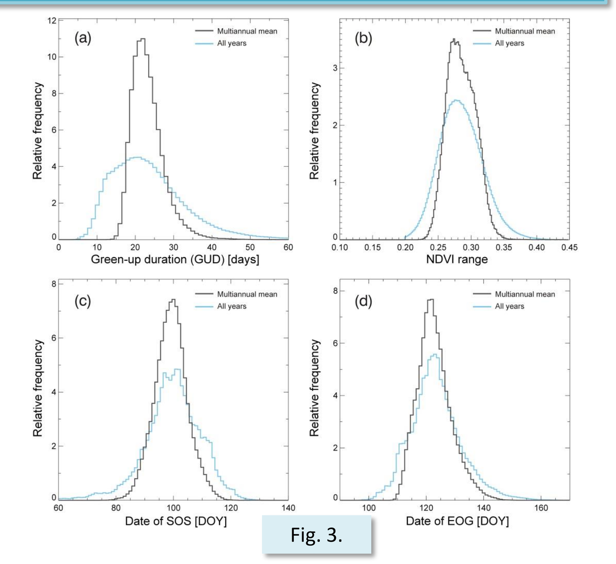

Fig. 3.

Extent of areas with the shortest GUD

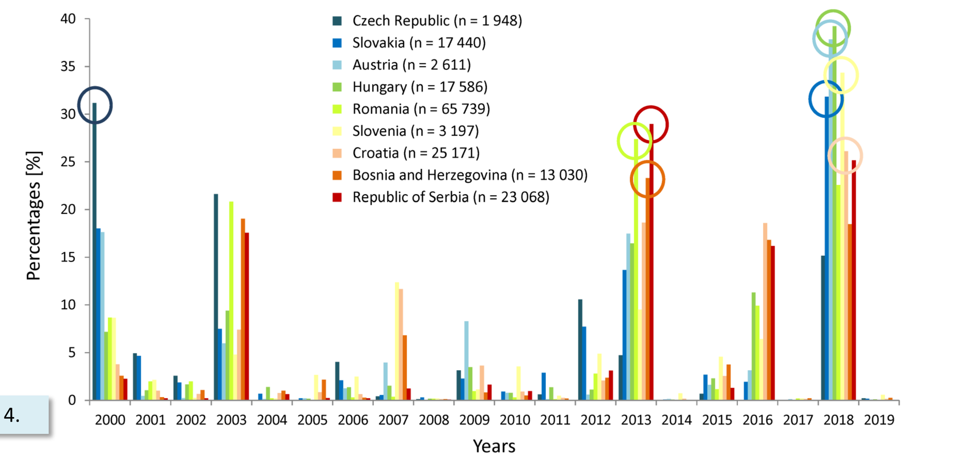

Fig. 4.

Percentages of the deciduous broadleaf forested pixels showing the **shortest green-up duration** in each year:

- in Hungary, Austria, Slovenia, Slovakia, and Croatia the shortest GUD affecting the largest area occurred unequivocally in 2018,
- in Czechia, the year 2000 showed the largest area with the shortest GUD,
- in Bosnia and Herzegovina the year corresponding to the largest affected area was 2013,
- in Romania and Serbia, the shortest mean GUD occurred in 2018 (Fig. 5), while the year associated with the largest area with the shortest GUD was 2013.

Interannual variability of GUD

For the whole domain:

- **the shortest mean GUD: in** 2003, 2013, 2016 and **2018** (with 14.5 days in 2018)
- **the longest mean GUD**: **in 2017** (with 32.7 days) and **2019** (with 31.0 days)

However, differences between countries are large.

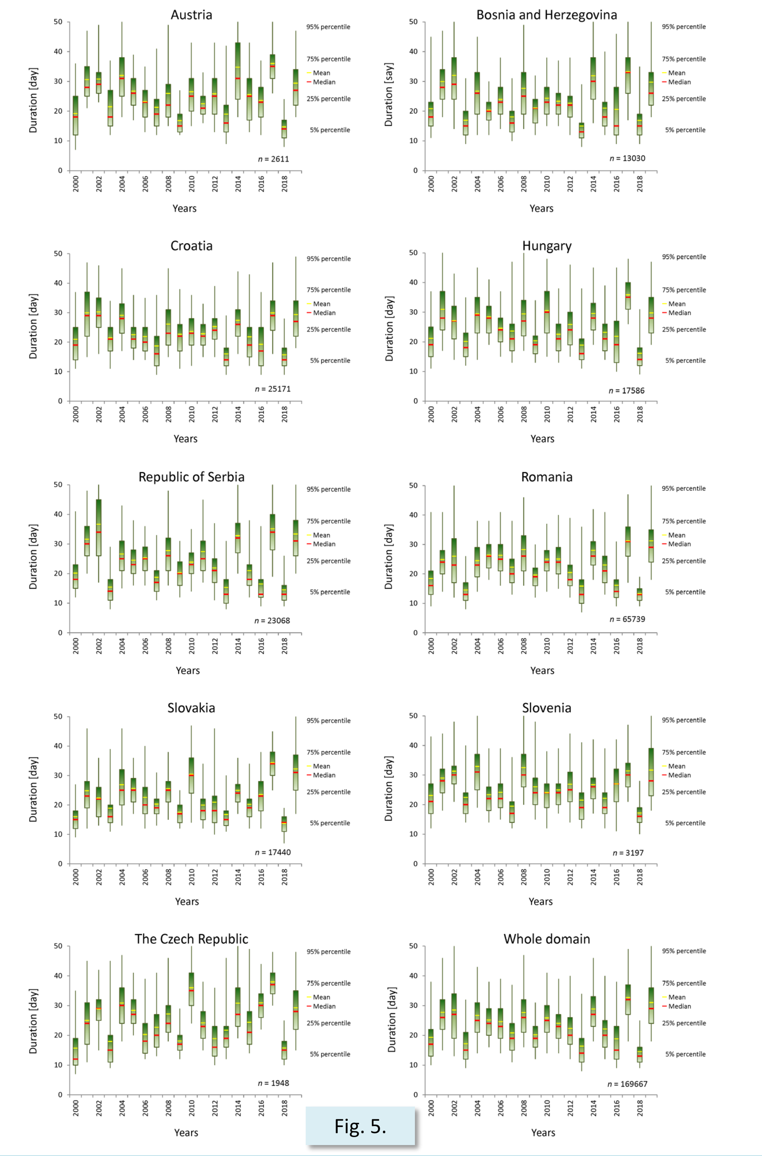

Fig. 5.

Modeling of green-up duration

Modeling approach

Table 1 shows the equations and the performance metrics of the constructed models for the GUD. The averaging period is shown in the subscript of the variables (BSOS and ASOS indicate mean meteorology *before* and *after* the SOS with 8-8 days, respectively, while GU indicates mean meteorology during the whole *green-up* period (from SOS to EOG). Models with gray background (M5, M7, M9) are purely diagnostic (explanatory) models, while the others are prognostic models.

- The main explanatory variable is the SOS date, explaining 38.3% of the GUD variability (*RMSE*=8 days),
- addition of the elevation and its square to the model increased the explained variance to 47.8% (*RMSE*=7.34 days),
- „the best" prognostic model is based on the meteorology during the green-up and also before,
- T_{max} alone improves the models significantly,
- Without the knowledge of the SOS the model performance is much weaker,
- delayed SOS implies a faster greening with shorter GUD.

		Model	Model equation	*R*	*R*²	*RMSE*
		M0	GUD = $\overline{GUD}$, (*null* model; in this study: $\overline{GUD}$ = 23.73 days)	0	0	10.17
With SOS (*relative time approach*)	No meteorology	**M1**	$GUD = 85.50 - 0.619 \cdot SOS$	0.619	0.384	7.99
		M2	$GUD = 94.93 - 0.006 \cdot DEM + 1.7 \cdot 10^{-5} \cdot DEM^2 - 0.735 \cdot SOS$	0.692	0.478	7.34
	Meteorology before SOS	**M3** Only Tmax before SOS (last 8 days)	$GUD = 100.29 - 0.009 \cdot DEM + 1.8 \cdot 10^{-5} \cdot DEM^2 - 0.630 \cdot Tmax_{BSOS} - 0.676 \cdot SOS$	0.718	0.516	7.06
		M4 Meteorology before SOS (last 8 days)	$GUD = 94.48 - 0.009 \cdot DEM + 1.9 \cdot 10^{-5} \cdot DEM^2 + 0.099 \cdot Tmax_{BSOS} - 0.624 \cdot Tmin_{BSOS} - 0.823 \cdot Rad_{BSOS} - 0.580 \cdot SOS$	0.728	0.530	6.96
	Meteorology after SOS	**M5** Only Tmax during green-up	$GUD = 101.44 - 0.015 \cdot DEM + 2.0 \cdot 10^{-5} \cdot DEM^2 - 1.173 \cdot Tmax_{GU} - 0.547 \cdot SOS$	0.740	0.547	6.83
		M6 Only Tmax after SOS (first 8 days)	$GUD = 96.32 - 0.013 \cdot DEM + 1.9 \cdot 10^{-5} \cdot DEM^2 - 0.850 \cdot Tmax_{ASOS} - 0.578 \cdot SOS$	0.746	0.556	6.76
		M7 Meteorology during green-up	$GUD = 94.00 - 0.014 \cdot DEM + 1.4 \cdot 10^{-5} \cdot DEM^2 - 2.278 \cdot Tmax_{GU} + 1.393 \cdot Tmin_{GU} + 2.036 \cdot Rad_{GU} + 1.731 \cdot Prec_{GU} - 0.747 \cdot SOS$	0.782	0.611	6.33
		M8 Meteorology after SOS (first 8 days)	$GUD = 94.24 - 0.013 \cdot DEM + 1.9 \cdot 10^{-5} \cdot DEM^2 - 0.660 \cdot Tmax_{ASOS} - 0.256 \cdot Tmin_{ASOS} - 0.036 \cdot Rad_{ASOS} + 0.168 \cdot Prec_{ASOS} - 0.573 \cdot SOS$	0.747	0.558	6.75
	Meteorology before and after SOS	**M9** Meteorology during green-up + before SOS (last 8 days)	$GUD = 82.73 - 0.013 \cdot DEM + 1.5 \cdot 10^{-5} \cdot DEM^2 - 3.085 \cdot Tmax_{GU} + 2.821 \cdot Tmin_{GU} + 2.806 \cdot Rad_{GU} + 1.561 \cdot Prec_{GU} + 1.479 \cdot Tmax_{BSOS} - 2.075 \cdot Tmin_{BSOS} - 1.387 \cdot Rad_{BSOS} - 0.644 \cdot SOS$	0.805	0.649	6.02
		M10 Meteorology after SOS (first 8 days) + before SOS (last 8 days)	GUD = 95.74 – 0.013 · DEM + 1.9 · 10–5 · DEM2 – 0.200 · TmaxASOS – 0.515 · TminASOS – 0.384 · RadASOS + 0.098 · PrecASOS – 0.364 · TmaxBSOS + 0.110 · TminBSOS – 0.177 · RadBSOS – 0.513 · SOS	0.756	0.572	6.64
Without SOS (*absolute time approach*)	Meteorology based on calendar dates	**M11** Meteorology based on calendar days (1st of Febr – 15th of March)	$GUD = 26.52 - 0.021 \cdot DEM + 2.2 \cdot 10^{-5} \cdot DEM^2 - 0.958 \cdot Tmax_{Febr1} + 1.644 \cdot Tmax_{Febr2} + 0.034 \cdot Tmax_{March1} + 0.989 \cdot Tmin_{Febr1} - 1.111 \cdot Tmin_{Febr2} - 0.095 \cdot Tmin_{March1} + 1.586 \cdot Rad_{Febr1} - 1.082 \cdot Rad_{Febr2} - 0.379 \cdot Rad_{March1} - 0.465 \cdot Prec_{Febr1} + 0.603 \cdot Prec_{Febr2} - 0.924 \cdot Prec_{March1}$	0.358	0.128	9.48

Table 1.

Limitations of modeling

The performance of the model M9 (the *best* model) as function of the length of BSOS averaging period shows that, increasing the length of the averaging period further backwards from the SOS has its limits, and for periods longer than 8 days the improvement in model performance is small.

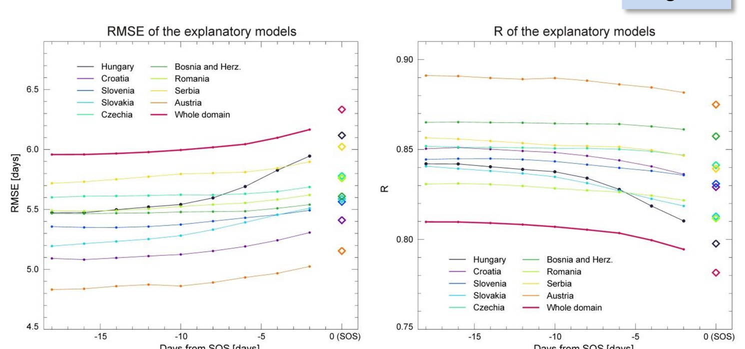

Fig. 9.

Drivers of the green-up duration

Meteorological variables

The linear correlation coefficients (*R*) between the area-averaged mean yearly GUD and the mean meteorological variables for the 16-day time period prior to SOS of the whole domain during 2000–2019 **support the selection of the influential periods of the meteorological variables.**

Two main periods are distinguished:
- before the SOS,
- during the green-up (until the EOG).

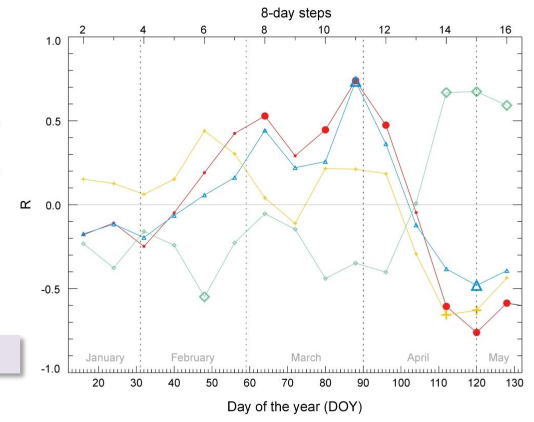

Fig. 6.

Start of the Season (SOS)

The linear correlation coefficients (*R*) the GUD and the timing of SOS at the pixel-level, we obtained an *R* value of the -0.62 for the whole domain. Calculating the correlations by elevation classes with 100 m resolution in elevation, the *R* values for the whole domain vary between -0.62 and -0.83. The stronger correlation representative at elevations above 700 m indicates that **the importance of SOS in determining the green-up duration is increasing.**

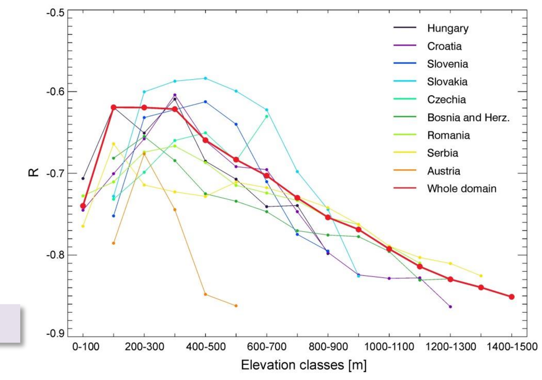

Fig. 7.

Elevation

There is a **clear elevation dependency of GUD** for the deciduous broadleaf forests for each year separately, and for all years together within the whole study area, emphasizing **a large interannual variability**. In general, deciduous broadleaf forests in the research area located between 400 and 500 m altitude show the shortest GUD, with a mean of 22.2 days, while those at 0–100 m and at 1400–1500 m reveal longer with mean of 27.9 and 31.4 days, respectively.

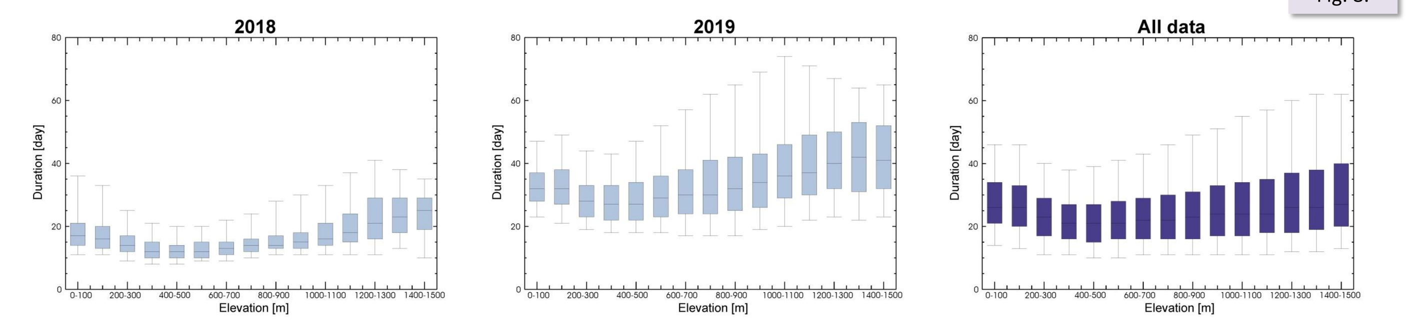

Fig. 8.

Conclusions

- Our results clearly showed that **there is considerable interannual variability in the green-up duration (GUD)** of the deciduous broadleaf forest during 2000–2019 in the wider region of the Carpathian-Basin.
- The **last three years had, on average, the shortest (2018) and the two longest (2017 and 2019)** recorded green-up durations in the region.
- Observed variability **was partially attributed to the meteorological conditions**, namely to the extreme weather events occurring during the spring green-up period, having a strong effect on the duration.
- The relationship between the SOS and the green-up duration reveals that the **SOS also played an important role as a driver**.
- Our results also reveal **considerable elevation dependency** both in the green-up duration and also in its correlation with SOS.
- **Multiple linear regression models** based on the SOS and the meteorological variables **were also created** to explain and predict the green-up duration.
- **Earlier SOS implies longer GUD**, while delayed SOS is associated with short GUD, which means that the benefits of climate change, possibly resulting in a longer growing season, could be smaller than anticipated.
- The results indicate the **complexity of processes** that drive the leaf unfolding.

For more details see: **Kern et al., 2020, AFM. doi:10.1016/j.agrformet.2020.107969**

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Acknowledgments

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