Final report of OTKA FK-128709 project

(2018–2023)

Remote sensing based detection of the effects of biotic and abiotic factors on vegetation activity in the Carpathian Basin

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In the present OTKA FK project the main emphasis was on the following interrelated research aims:

1. Describing plant phenology by different metrics;
2. Determination of critical time periods that affect plant status in Central Europe (abiotic factors);
3. Construction of conceptual models for modelling vegetation status based on abiotic factors;
4. Remote sensing based investigation of plant status changes caused by insects (biotic factors);
5. Synergistic use of the constructed conceptual models and the insect damage analysis;
6. Quantification of the possible future effect of climate change on the plant status based on climate model data and the results of the phenology and critical time period analysis.

In line with the listed aims an extended overview of the research made in the frame of the project, with references to the published results, is presented here.

(1) Describing plant phenology by different metrics

In our research, we used different remote sensing based metrics for the description of plant phenology, such as (i) the state of the vegetation (expressed with vegetation indices) in a given period of the year; or (ii) other characteristics of the phenology (see below).

Calculation of the start of the season (SOS) based on different metrics (*Dávid et al., 2021*) and determination of the green-up duration (GUD) of deciduous broadleaf forests within the wider region of the Carpathian Basin was made (*Kern et al., 2020a; 2020b*). The speed of the spring leaf unfolding was also investigated in detail, but we found that the length of the spring green-up is a more reliable characteristic with fewer misleading and false results. The research on the topic of GUD (*Kern et al., 2020a; 2020b*) was based on the exceptionally long and unique MODIS dataset with 500-meter spatial resolution, covering 2000–2019. Beyond the characterization of the spring GUD over 20 years additional modelling work was also elaborated and presented to describe (using meteorology as explanatory variables) and forecast the expected GUD of broad-leaved forests of 9 countries in the Carpathian Basin. Multiple linear regression models based on the SOS and the meteorological variables were created to explain and predict the green-up duration (*Kern et al., 2020a; 2020b*). Our results clearly showed that there is considerable interannual variability in the green-up duration (GUD), where the last three years had, on average, the shortest (2018) and the two longest (2017 and 2019) recorded green-up durations in the region. The observed variability in GUD was increasing with time and could be mostly attributed to the meteorological conditions. The relationship between the SOS and the green-up duration revealed that the SOS also played an important role as a driver (earlier SOS implies longer GUD, while delayed SOS is associated with short GUD). Considerable elevation dependency was also found both in the green-up duration and also in its correlation with SOS.

With respect to the SOS, different models were tested to describe the timing of the leaf onset and their sensitivity to the input meteorological driving variables (*Dávid et al., 2021*). The results indicate that the simulated timing of leaf onset primarily depends on the model structure choice, with only a secondary contribution from the driving meteorological dataset.

Additional research was also made to investigate the species, elevation and aspect dependence of the SOS and their trends in a mountainous forested region (*Marjanović et al., 2021*); or the phenology of the Hungarian grasslands (*Dávid et el., 2022*). The elaborated methodology to calculate SOS values was applied to other datasets as well, such as the NDVI3g (*Dávid et el., 2021a; 2021b*).

Plant phenology was also characterised by multiannual mean and interannual variability curves during the year for eight different natural or semi-natural ecosystem categories in Hungary based on 21-year-long (2000–2020) datasets (*Kern et al., 2022a; 2022e*), emphasizing the role of the weather and soil water content conditions on the mean plant functioning during the vegetation period.

2. Determination of critical time periods that affect plant status in Central Europe (abiotic factors)

We identified ecosystem-specific critical climate periods as short-term periods during the year, which are predominantly indicators of the observed interannual variability of the vegetation state and might be considered responsible for the accuracy of prediction (*Kern et al., 2022a; 2022e*). Those critical climate periods were determined based on 21-year-long (2000–2020) remote sensing, meteorological, and soil water content datasets. We focused on eight different natural or semi-natural ecosystem categories according to the NÖSZTÉP ecosystem database, which are dominant in Hungary. The results of the developed methodology were presented for NDVI and LAI (*Kern et al., 2022a; 2022e*), but were calculated for several other indices as well (LAI, SAVI, FPAR, NIRv, GPP, NPP). The identified periods can be associated with the long-term (i.e., climatological time scale) interaction between climate anomalies (realized as weather) and the lifecycle of the plants at a given location. Our results emphasize the diverse behaviour and adaptation strategy of the different vegetation types (forests versus grasslands), but even between the different ecosystem categories.

The effect of the abiotic factors (meteorological and soil water content conditions) was also tested on the crop yield estimation of maize, winter wheat, sunflower, and rapeseed using 16 different vegetation indices calculated from remote sensing data (*Bognár et al., 2022*). The information on the environmental conditions served to improve the crop yield estimation, and resulted also in the identification of the most influential periods based on the used 21-year-long (2000–2020) remote sensing, meteorological and soil water content datasets.

3. Construction of conceptual models for modelling vegetation status based on abiotic factors

During our research, in order to understand vegetation functioning, the satellite-based detection of changes in phenology was intertwined with modelling approach. A considerable effort was put into building and testing large number of different models using meteorological and soil water content datasets as predictors to support the selection of the "best" mathematical model to describe the (i) state of the vegetation in a given period of the year through vegetation indices, or (ii) other vegetation-related variables according to the specific aim.

Multiple linear regression models were constructed based on our *most influential period* (MIP) technique, where the models were based on those variables and periods which had the strongest correlation (expressed with the *Pearson* R values) with the given vegetation-related characteristic (*Barcza et al., 2020; Kern et al., 2020*). The relationships between the vegetation indices and the environmental variables with fine temporal resolution enabled the determination of those periods during the year when the vegetation showed significant sensitivity of any environmental condition before (*Kern et al., 2020a; 2022a; Barcza et al., 2020*). The methodology to determine the critical time periods was elaborated also using the relationship between the vegetation-related characteristics (presented for NDVI and EVI) and the environmental variables (*Pearson* R values), with different temporal averaging and moving window periods (*Kern et al., 2022a*).

To reduce the large number of independent variables during modelling, the *Boruta* method was used to select the environmental variables in which the former periods had relevant roles in affecting the vegetation state (*Kern et al., 2022a*). The *Boruta* method quantifies the importance of the driving climate variables using random forest classification. In our research, *Boruta* was used with six mean climate variables averaged over 32 days for five former periods with different time lags (*Kern et al., 2022a*).

The constructed models were calibrated and then validated by the application of the leave-out-one-year (LOOY) cross-validation technique (*Kern et al., 2020a; 2022a*). In the LOOY validation, the model was calibrated with a dataset from which one calendar year of the data was omitted year by year. Model predictions were then tested against the observations in the year that was left out, and the procedure was repeated for all years of the validation dataset. The presented modelling approach enabled us to select the best models as well as the corresponding set of parameters needed for the successful modelling of the vegetation state.

4. Remote sensing based investigation of plant status changes caused by insects (biotic factors)

In addition to the effects due to the abiotic factors, we also investigated plant status changes caused by biotic factors such as insects. Our primary focus was the new and invasive North American oak lace bug (*Corythucha arcuata*, Say 1832) (OLB), which spreads rapidly and shows no signs of receding after establishment, jeopardizing the European oak forests (*Kern et al., 2019b; 2019e; 2021a; Marjanović and Kern, 2021; Paulin et al., 2020*). We designed and applied two novel methods for detecting and assessing the impact of the oak lace bug during the period 2000–2019 based on MODIS NDVI with 250 m spatial and 8-day temporal resolution. The first detection method was based purely on the caused NDVI decrease, therefore has the potential to be used in near real-time detection. According to our results, the OLB causes a remarkable infestation, dramatically reducing the NDVI from July onward, which indicates a strong decrease in photosynthetic activity.

The possibilities of assessing the damage caused by the defoliation of the gypsy moth (*Lymantria dispar*, Linnaeus, 1758) in the Hungarian oak and beech forests were also studied, based on those areas where the infestation was *in situ* detected. Interestingly, after the 2005 outbreak (*McManus and Csóka 2007*), there were no major gypsy moth outbreaks in Hungary in the subsequent years, despite the usual outbreak cycle of 8-13 years (*Baukouvala et al 2022*). At the time of the writing of the proposal for this project (2017/2018) gradation and outbreak of gypsy moth was expected again, but until the end of this project it had not occurred. Therefore, we decided to focus on and put all of our efforts into the detection of the oak lace bug.

5. Synergistic use of the constructed conceptual models and the insect damage analysis

To detect the spread and impact of the oak lace bug infestation, we elaborated a second method as well. This method is based on the residual Z-score of the NDVI models (build for this purpose) using daily meteorological and soil water content data as independent variables. Unlike the above described method based only on remote sensing, this method aimed at improved damage assessment by decoupling the effects of the OLB from those caused by the environmental drivers, as abiotic factors.

In order to decouple the effect of the meteorology from the state of the vegetation in a given period of the year, several different NDVI models were created and tested. Multiple linear regression models were constructed based on our most MIP technique, similarly to our previous published studies, while the Least Absolute Shrinkage and Selection Operator (LASSO) technique selected the variables and their periods during the year based on a statistical approach. The results showed that the LASSO technique is a promising tool in NDVI modelling using meteorological and environmental data. The performance of the models based on the MIP of the different variables showed slightly worse results, although their application is more intuitive.

Methods developed within this project were used for the successful reconstruction of the spread of the OLB, the speed of its spread, as well as identification of the infestation origin and most likely vector (*Kern et al., 2021a; Marjanović and Kern, 2021*).

6. Quantification of the possible future effect of climate change on the plant status based on climate model data and the results of the phenology and critical time period analysis

Our conceptual, multiple linear regression models were used to investigate the expected future changes based on the new versions of the FORESEE database (Open Database FOR ClimatE Change-Related Impact Studies in CEntral Europe, *Dobor et al., 2015*). As the annual crop yields strongly depend on the ongoing meteorological conditions, we investigated the weather-induced effect on winter wheat crop yield (*Kern et al., 2022b*) using our previously published model (*Kern et al., 2018*) based on the ensemble of 14 RCM simulations. Our results indicate that for Hungary the ensemble mean effect of the weather on the winter wheat crop yield would be negative, causing a decrease. We need to emphasize that this does not necessarily mean a real decrease in the overall winter wheat yield. Improving agrotechnology (introduction of new cultivars, use of mineral fertilizers, pesticides/herbicides and improving machinery), and also increasing level of atmospheric CO_2 concentration is expected to increase the overall winter wheat yield, but the climate change would work against it. The consistency of the ensemble results gives confidence that the impact of climate change on the winter wheat yield in Hungary will be negative and considerable. This is an important message as the predicted decline in crop yield caused by the changing weather has to be compensated with the same magnitude by the positive effects (listed above).

To estimate the possible changes in the timing of the start of the growing season (SOS) of the Hungarian broadleaf forests in the future, we applied a simple growing degree-day model optimized and validated for the Hungarian forests, published in our previous research (*Dávid et al., 2021*). We investigated the changes in SOS based on the new versions of the FORESEE database, using ensemble mean approach of the available projections (*Kern et al., 2022b*). Based on our results, the estimated mean advance of SOS for the Hungarian forests due to the expected climate change is significant, which is in accordance with other studies.

Additional research is ongoing to study the effect of climatic warming on tree growth (*Móricz et al., under preparation*).

The above-listed works were based and heavily relied on the time and computer resource (RAM) demanding pre-processing of the large remote sensing datasets, and the preparation of additional datasets, e.g., the meteorological or the land cover and ecosystem map datasets. The used vegetation characteristics (NDVI, EVI, SAVI, LAI FPAR, GPP, and NPP) derived from different official MODIS products (MOD09, MOD15, MOD17, and MOD43) were updated and re-processed on a yearly basis with the finest spatial and temporal resolution, resulting in a final database covering the period of 2000–2022 for the Carpathian Basin. At the beginning of the project, these meant the application of the Collection 6 MODIS products, but with the gradual release of the new Collection 6.1 datasets, the new datasets were also downloaded and processed. The raw data were processed using rigorous and fundamentally different quality assurance methods for each product, ensuring the quality of the research. The created pre-processed database of the vegetation-related characteristics contributed to other studies as well, like investigating the influence of vegetation on the occurrence and time distributions of aerosol particle formation (*Salma et al., 2021; Thén et al., 2021*), or investigating the effect of tillage and crop type on soil respiration (*Gelybó et al., 2022*). Sentinel-2 MSI datasets were also downloaded for the whole available period and area of Hungary and Northern Croatia, and were used for local and fine-scale monitoring of the actual state of the vegetation and investigating for the applicability of detecting the damage caused by the oak lace bugs (*Kern et al., 2019e*).

The task of the FORESEE meteorological database development and maintenance was passed from the initial developer (Laura Dobor) to the PI (Anikó Kern) in 2018, in the frame of the project. The continuation of the FORESEE database (*Kern et al., 2019a; 2021b; 2022d; 2022b*) was not just a key component of our research focusing on the effect of the weather on phenology (*Dávid et al., 2020a; 2020b; 2021a; 2021b*; *Kern et al., 2020a; 2020b; 2021; 2022a*) and vegetation productivity (*Bognár et al., 2022; Fodor et al., 2020; 2021; Marton et al., 2020; Ostrogović Sever et al., 2021, Móricz et al., under preparation)*, but relevant to other researchers and studies as well (for a detailed list see *Kern et al., 2019a* and *2022b*). Significant developments and considerable works were also made resulting in completely new versions (the v4.0 and the embedded FORESEE-HUN v1.0) with increased spatial resolution, geographic domain, and new future datasets (*Kern et al., 2022b; 2022c*). Updating the observational part of the database on a yearly basis according to the latest E-OBS/HUCLIM datasets and including new and bias-corrected climate projections (14 EURO-CORDEX) and scenarios (RCP4.5 and RCP8.5) for the future, established also the future of the FORESEE database, leading to other projects as well (e.g., National Multidisciplinary Laboratory for Climate Change, RRF-2.3.1-21-2022-00014). Beyond the basic meteorological variables, additional variables were also calculated at a daily level (both for the past and the 28 model combinations for the future) using the Mountain Microclimate Simulation Model (MT-CLIM) v4.3 consistently for the entire 1950–2100 period. The created datasets have a total size of more than 1.6 TB, which are available to the public as well (*Kern et al., 2022b*). The website of the database was continuously updated by the PI for the public as well (https://nimbus.elte.hu/FORESEE/). A research paper on the new versions of the FORESEE database, their evaluation, and example applications of the multiple linear regression models for the future was submitted to the Q1 journal "*Climate Services*" of Elsevier (*Kern et al., 2022b*) in September 2022, which is at the present still under review.

Since the remote sensing observations determined the grid of our investigations, all additional datasets had to be resampled to the grid of the satellite data (primarily MODIS HKM and QKM). Great efforts were made on the downscaling of the environmental data (meteorological and SWC) to the finer spatial grid (of MODIS) based on our previously elaborated method within OTKA PD-111920, *Kern et al., 2016*), and on the resampling of the different land cover (CLC2012, NÖSZTÉP), species datasets (Croatian Forest Species) and *in situ* datasets to the coarser spatial grid (of MODIS). The determined r*eliable pure* pixels (stable in time, and containing only one PFT), as a result of the synergistic use of CLC2012 and the MODIS Land Cover product (MCD12) served as a basis ancillary dataset during the beginning of the research, to make land cover specific investigations (*Bognár et al., 2022; Dávid, 2021a; Kern et al., 2020a; 2020b; Kern and Lichtenberger, 2018; Salma et al., 2021; Thén et al., 2021*). Later, our research exploited the great possibility of the newly published NÖSZTÉP ecosystem map, too, with fine spatial resolution. The derived and accurate ecosystem shares of the 46 NÖSZTÉP categories in every MODIS pixel supported precise ecosystem-specific investigation as well (*Dávid et al., 2022; Kern et al., 2021; 2022*). The knowledge gained during the work with the new NÖSZTÉP ecosystem database within the project contributed to other research as well, where the essential information on vegetation type around a tall-tower flux site was used in greenhouse gas related research (*Haszpra et al., 2022*), not strictly related to the project.

Contrary to the natural or semi-natural vegetation (forest and grasslands), agricultural crop-specific investigation can only be executed if the planted crop type is known in a particular year. Involving a Ph.D. student (Edina Birinyi, Eötvös Loránd University, Doctoral School of Earth Sciences) in the remote sensing-related research, an additional stream of investigations was started in the field of crop growth and weather interactions (*Birinyi et al., 2021; 2022a; 2022b; 2022c*). These remote sensing-based works rely heavily on the yearly parcel-level crop type classification database provided by the Lechner Knowledge Center (by Edina Birinyi and Dániel Kristóf). Due to the new collaboration built with the Lechner Knowledge Center during the project, the research in this area is ongoing, and further results are expected in the next years.

The main results of the project are summarized with additional links at the website of http://sas2.elte.hu/vegetation_EN.html as well. Climatological fields derived from the processed MODIS NDVI, EVI, LAI, FPAR, GPP, NPP, and from the basic meteorological variables (FORESEE mean temperature and precipitation) are also published at https://nimbus.elte.hu/Vegetation_CE/ based on the latest datasets, illustrating the inter-annual variability in the vegetation and climatic conditions over 2000–2022.

In the frame of the project, the PI was a co-convener at three international conferences (EGU 2022, Green 2022, EGU 2023). The wider audience was also targeted during dissemination activities in the form of lectures, in many cases the PI as an invited lecturer (*Kern, 2019c; 2019d; 2019e; 2022a; 2022b; 2022c*). However, participating in conferences was hardened by the fact that the COVID-19 epidemic notoriously set back the implementation of conferences and noticeably slowed down the turnaround time for reviewing papers.

During the project, the PI supervised one MSc work (*Balázs, 2020*) on the topic of satellite-based vegetation indices. At present, she supervises one Ph.D. student (*Birinyi, E.*) investigating the effects of drought and inland water on vegetation state, and one BSc student (*Szabó, F.*), also in the field of remote sensing.

Main results:

The main results of the project can be summarized as follows. (1) Providing new insight into the vegetation-climate interactions through different applications of the MODIS-based vegetation-related characteristics for the period of 2000−2020; (2) Development of methods to simulate vegetation state and other characteristics of the plant phenology as the function of environmental conditions (abiotic factors); (3) Based on the models development of methodology to quantify the effects of biotic factors as well; (4) Quantification of the interannual and spatial variability of green-up duration (GUD), leaf onset timing (SOS), and vegetation state; (5) Identification of critical climate periods that substantially control vegetation state in terms of climate variables; (6) Detailed description of the infestation and spread of the invasive oak lace bug; (7) Construction of the new and updated version of the FORESEE database, as a reinforcement of the importance of the meteorological variables, highlighting the need for climate datasets with fine spatial and temporal resolution; and (8) Demonstrating the applicability of multiple linear regression models for the future with ensemble mean approach.

Usability:

(1) The elaborated detection and modelling methods can be used in other studies as well to model the vegetation state or other vegetation-related characteristics according to the environmental conditions; (2) to map insect spread and to assess the damage caused by pest infestation in term of productivity; (3) the interannual variability of the vegetation-related characteristics demonstrates the magnitude of the effect of the extreme climate conditions on vegetation during the last 2 decades; (4) the presented critical climate periods can foster better understanding of plant functioning; (5) the modelling works can facilitate the implementation of the derived green-up characteristics in the processed-based phenology models, such as the BIOME-BGCMuSo model; (6) the free to the public FORESEE database can support several different research and impact studies both for the past, and (7) for the future using ensemble mean approach.

References (works within the frame of the project):

Peer-reviewed publications in English:

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Sum of the impact factors: 63.2
Number of D1 papers: 4
Number of Q1 paper: 5
Number of Q2 papers: 3

Submitted or under submission publications:

Kern, A., Dobor, L., Hollós, R., Marjanović, H., Torma, Cs.Zs., Kis, A., Fodor, N., Barcza, Z., 2022b. Seamlessly combined historical and projected daily meteorological datasets for impact studies in Central Europe: the FORESEE v4.0 and the FORESEE-HUN v1.0. Submitted to *Climate Services* (Elsevier) on 16th of September, 2022. Under Review.

Móricz, N., Garamszegi, B., Kern, A., Mészáros, I., Illés, G., Eötvös, Cs., Hirka, A., Németh, T.M. Effect of climatic warming on tree growth of Quercus petraea (Matt.) Liebl. and Quercus cerris L. on climatically contrasting sites. Under preparation.

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