Application of satellite remote sensing data to characterize vegetation dynamics within the Carpathian Basin

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Final report

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Introduction

The terrestrial biosphere has strong connection with the climate of the Earth and has a driving role in its stability through feedback processes (*IPCC, 2013*). Quantifying plant production and understanding the processes behind variability of plant status and production is of high importance in general, and also in the context of climate change (*IPCC, 2013*). Plant production and the related ecosystem services are affected by the complex interactions between plant growth and the meteorological parameters, soil processes, disturbances and other factors. The causal relationship between some well documented anomalous weather conditions and plant status is well recognized (*Ciais et al., 2005*), however, the exact cause of the observed variability of plant health and growth is not well quantified due to the complexity of the driving variables and the parallel changes in many meteorological elements. Therefore, it is essential to have up-to-date and accurate information about the current state of the vegetation and to analyze the causes of the detected changes. The best technique to provide data with high temporal frequency about the state of the vegetation with global coverage is remote sensing.

The main aim of the present research was to perform a comprehensive investigation of the vegetation and its variability within the Carpathian Basin based on remote sensing data, and to investigate how the climate variability influenced the vegetation of the region during the past decades. The performed work was based on vegetation related characteristics derived from the data of the MODerate resolution Imaging Spectroradiometer (MODIS) on board EOS-AM1/Terra and EOS-PM1/Aqua satellites, and on the new, so-called NDVI3g datasets created by the Global Inventory Modelling and Mapping Studies (GIMMS) from the data of the Advanced Very High Resolution Radiometer (AVHRR) onboard the series of the NOAA meteorological satellites. To study the effect of climate variability in the region meteorological data were also used in the research (mainly temperature and precipitation data from the 2.1 and 2.3 versions of the freely available FORESEE database (*Dobor et al., 2014*)). The primary investigation period was 2000-2016 due to the availability of the official MODIS products, while using the NDVI3g dataset the research was extended to cover the 1982-2016 time period as well.

MODIS data capable to quantify different plant related characteristics were retrieved from two different sources. On one hand, the latest version (C6) of the vegetation related official MODIS products were used with the finest common resolution. Those vegetation characteristics are the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) (as part of the MOD13 and MYD13 official MODIS products), Fraction of Photosynthetically Active Radiation Absorbed by Vegetation (fAPAR) and Leaf Area Index (LAI) (as part of the MOD15 and MYD15 official MODIS products), and Gross Primary Production (GPP) and Net Primary Production (NPP) (as part of the MOD17 and MYD17 official MODIS products). On the other hand, daily MODIS data recorded by the Direct Broadcast (DB) satellite receiving station of the Eötvös Loránd University (*Kern et al., 2014, Kern et al., 2016b*) were also applied to the studies. This latter dataset is routinely processed by the Principal Investigator (PI) since 2004, where the results are continuously available at the website http://nimbus.elte.hu/kutatas/sat/modis.html.

Based on the longest available time series with the finest spatial and temporal resolution, the performed research was the first that comprehensively evaluated and investigated the differences between the datasets and its connection with the variability of climate within the Carpathian Basin.

The first project year (October 2014 - September 2015)

In the first project year the work focused on the preparation of the complex dataset which were used in the project. Collection, pre-processing, quality control and data conversion of the data was essential part of the work. The collected and pre-processed dataset was used in pre-investigations to get rough information about the vegetation state within Hungary. Effect of sensor degradation was detected in the Collection 5 (C5) version MODIS product including NDVI and EVI data (MOD13), which caused false negative trend in the NDVI time series of forests in Hungary and Croatia during the 15 years (*Kern et al., 2015c*). The pre-processing of the 10 years long Direct Broadcast (DB) MODIS dataset, recorded by receiving station of the Eötvös Loránd University, was performed for the period of 2005-2014, and later for 2015 as well. Country averaged, land-cover specific NDVI values were also determined based on the derived dataset, enabling the creation of yearly NDVI curves.

In order to gain some insight into the relationship between environment drivers and plant functioning, first country averaged NDVI and EVI values were used for Hungary, revealing strong inter- and intra-annual variability of the overall plant state. The results indicate that the country averaged values and the range of the derived NDVI profiles are rather useful to study the overall state and phenology of the vegetation of Hungary, and to describe the average behaviour of the vegetation, and also to distinguish the different years under the effect of the different weather conditions (*Kern, 2015; Kern et al., 2015a*). Remarkable co-variations were also discovered with the meteorological data, showing that the mean precipitation and temperature of the growing season (May-October in the study) jointly modulate the fluctuations of growing season's mean NDVI and EVI in Hungary. Preliminary results of the pre-processed NDVI and EVI time-series were presented in a popular paper written in Hungarian (*Kern, 2015*), at the annual EGU meeting in Vienna as a poster (*Kern et al., 2015a*) and in the form of an oral presentation at the CSPP/IMAPP Users' Group Meeting in Darmstadt (*Kern et al., 2015b*).

During the first year of the project cooperation was established with the Croatian Forest Research Institute. Within the frame of this cooperation the remote sensing datasets were also used to study forests activity (its health and state) in Hungary and Croatia. The results showed that the MODIS NPP and GPP (C5.5 MOD17) products proved to be in good agreement with *in situ* eddy covariance data and field measurements, where better results can be expected for moist and "average" years, while for dry years our study indicates that MODIS underestimates productivity in lowland oak forests. The results of this joint work were presented on international conferences and workshops in the form of posters and lectures (*Kern et al., 2015c; 2015d; Marjanović et al., 2015a, 2015b, 2015c*).

The second project year (October 2015 - September 2016)

During the second project year the work focused primarily on the joint application and evaluation of the longest available, highly valuable NDVI3g and the MODIS NDVI dataset in the target area of Central Europe. A method was developed to perform statistical harmonization of NDVI3g and MODIS NDVI based on the higher radiometric accuracy of the sophisticated MODIS sensor and its finer spatial resolution against the AVHRR, using the overlapping period of 2000-2013. With statistical harmonization of NDVI3g with the latest version of MODIS NDVI datasets, a harmonized (or in another name, a MODIS-adjusted) NDVI3g dataset were created for the period of 1982-2013, which can be used for different vegetation related studies in Central Europe.

In-depth analysis of the quality and suitability of the widely used NDVI3g dataset was also performed for the estimation of different vegetation characteristics of the NDVI in a regional scale, for the region of Central Europe. Additionally, NDVI anomalies were also compared and evaluated together with simple climate sensitivity metrics, which was performed based on temperature and precipitation data of the FORESEE meteorological database. To perform an even better comparison of the meteorological anomalies and the vegetation related characteristics, the daily precipitation and maximum/minimum temperature fields at 1/12° × 1/12° grid were resampled to the 8-day temporal and 1 km × 1 km spatial resolution of the MODIS products, using SRTM elevation data as well (*Kern et al., 2016d*).

The novel character of this study is the handling of Collection 6 (C6) MODIS data as reference, which means that the vegetation metrics are evaluated against the MODIS NDVI, and phenological

features were studied separately for the original NDVI3g, the harmonized NDVI3g, and for the MODIS NDVI dataset. The annual cycle of the vegetation was studied from different aspects (such as mean seasonal NDVI profiles, start, end and length of the growing season, magnitude and timing of peak NDVI), where a methodology to estimate start and end of the growing season was developed as well, enabling further in-depth analysis of the climate-vegetation coupling. Systematic deviations between the NDVI3g and the MODIS NDVI were analyzed, showing that (1) the original NDVI3g has limited applicability in Central Europe, which was also implied by the significant disagreement between the NDVI3g and MODIS NDVI datasets, (2) the harmonization of NDVI3g with MODIS NDVI is promising since the newly created dataset showed improved quality for phenology timing detection and the other vegetation metrics. The research included the evaluation of the interannual variability, detection of the anomalies, and the spatial examination of the statistics and climatology of the vegetation indices from the different data sources. We proved that the anomalies are not reproduced well by the NDVI3g, even by the harmonized dataset, which warns us that the anomaly detection with NDVI3g should be handled with caution in Central Europe. The NDVI3g dataset is still unexploited in Central-Europe, therefore the produced MODIS-adjusted NDVI3g dataset involves many possibilities for the Carpathian Basin. The results can support end-users of NDVI3g in Central Europe to select appropriate phenology metrics and provide information about its expected quality.

The results were presented in the open access, peer-reviewed, Q1 journal *Remote Sensing* (*Kern et al., 2016d*). The created harmonized database was published at the website of *Zenodo* (*Kern et al., 2016e*), providing unique DOI reference number to this open access dataset. The database is also available at http://nimbus.elte.hu/NDVI_CE/.

Using the derived finer resolution meteorological data and the newer C6 MODIS NDVI datasets, the studies were continued to investigate the effect of meteorological data on the NDVI anomalies, where the results were presented on international conferences in the form of poster and lecture (*Kern et al., 2016a; 2016c*). The hypothesized lagged relationship between NDVI/EVI anomalies and the deviations of the environmental conditions from the multiannual mean were studied for the main land cover types (*Kern et al., 2016c,* presented as a key-note speaker) and separately only for the forest (*Kern et al., 2016a*) in the form of annual cycles of the linear correlation coefficient. The results suggest that the driving environmental conditions should be analyzed separately for these forests with different ecophysiology. The quality of the different GPP products was also examined and presented on international conferences and workshops (*Marjanović et al., 2016a; 2016b*).

To gain land cover specific results special emphasis were made on the derivation of the appropriate land cover classifications with the optimal grid resolution and on its resampling based on the 13-years long MCD12Q1 IGBP database with 500 m × 500 m spatial resolution (*Kern et al., 2016a*) and later also its joint application with the CORINE database (*Kern et al., 2017a; 2017c*).

The effects of climate variability on agricultural production and crop yield were studied preliminary based on time-series created from the pre-processed daily MODIS data recorded by the DB satellite receiving station of the Eötvös Loránd University, showing clear relationship between the weather and the crop yields of winter wheat based on NDVI time-series. The results were presented in the peer-reviewed Q1 *International Journal of Remote Sensing* (*Bognár et al., 2017*) and also on the CSPP/IMAPP User's Group meeting in the USA in the form of lecture, as an invited lecturer (*Kern et al., 2017d*). These works also demonstrated the suitability of the country-scaled studies. In the works of Bognár *et al.* (*2016*) and Kern *et al.* (*2017b,* presented at the conference of EGU) the applicability of the locally received, pre-processed direct broadcast (DB) MODIS data with the official MODIS products and the NDVI3g dataset for crop yield estimation were also compared and studied. The results showed the best applicability in case of DB MODIS data and a weakest in case of the original NDVI3g dataset, where the harmonized dataset shows similar applicability than the official MOD13 datasets. The results clearly demonstrate the applicability of the DB data in terms of temporal resolution, despite of the higher accuracy of the derived official MODIS products.

The third project year (October 2016 - September 2017)

The complex data processing work of the previous years resulted in a large database of pre-processed, quality controlled and temporally resampled remote sensing products for Central Europe (consisting of the vegetation related metrics of NDVI, EVI, LAI, FPAR, GPP, and NPP). A

public website containing the yearly mean and anomaly maps of the applied meteorological and vegetation related MODIS datasets during the investigated years of 2000-2016 within the Carpathian-Basin was also created (http://nimbus.elte.hu/Vegetation_CE/). Based on this dataset the vegetation state and its response to climate fluctuations were deeply analyzed in the third project year. The aim of this activity was to select and characterize typical and anomalous years (affected by extreme weather events) for the Carpathian Basin in Central Europe, based on the response of the vegetation using satellite based remote sensing data and meteorological observations.

Since the above listed indices provide diverse information about the vegetation activity and state, their joint application was proposed. The results show that plant status in terms of both positive and negative anomalies shows strong land cover dependency in Central Europe. This is most likely due to the differences in heat and drought resistance of the vegetation, and species composition. Relative anomalies were calculated for the selected years, making possible the selection and comparison of the anomalous years for the different land cover types of the investigated countries (Bosnia and Herzegovina, Croatia, Czech Republic, Hungary, Slovakia and Slovenia). However, the response of the vegetation is the result of complex interactions, depending not only on temperature and precipitation, but also on soil moisture, radiation, depth of the root zone, storage of carbohydrate reserves from previous years, insect outbreaks, etc. Correlation of anomalies with meteorological parameters was also studied. The results indicate that both the direction and the strength of the correlation strongly depend on the land cover type, indicating complex relationship between the vegetation and meteorological conditions. The selected country-specific extreme years (based on the effect of the weather on the vegetation) can serve as a basis for forthcoming research. The results for 2000-2014 were presented in the open access, peer-reviewed journal *SEEFOR* (*Kern et al., 2017a*) which is indexed by Web of Science, and for 2000-2016 at the annual EGU conference in the form of a poster (*Kern et al., 2017c*).

Tendencies in the NDVI values during the period of 1982-2013 and 2000-2013 based on the 32 years long NDVI3g (and its harmonized version) and the MODIS datasets were also performed and compared (presented at the EGU conference, *Kern et al., 2017b*), confirming the weaker applicability of the NDVI3g dataset in contrast to the MODIS datasets.

The investigation of the effects of climate variability on agriculture and crop yield was continued based on the official crop yield data from the Hungarian Central Statistical Office (at county level and country level). The anomaly of the crop yield of winter wheat, maize, oat, barley, rye and sunflower were studied together with the meteorology (using FORESEE database) for the period of 1986-2016 at county-level, and for the period of 1921-2016 at country-level (using the CRU database). A paper is under preparation that will summarize the results, which is planned to be submitted to a Q1 peer-reviewed Journal.

The research was extended to find areas in Hungary (separately for various land cover types) which represent the average conditions (in terms of meteorological parameters and NDVI) within the country for a given surface type, using a complex criterion system based on the mean temperature and precipitation data provided by the FORESEE database and the NDVI values of the NDVI3g datasets and the MODIS products. The results were presented in a workshop in the form of oral presentation (*Kern, 2017*).

The sensitivity of plant state to meteorological anomalies was also studied (*Kern et al., 2017e*), where the basic question was the following: can we identify differences between responses of plants in terms of their sensitivity? To answer this question we distinguished the effects of weather anomalies for areas with high and low climate variability, to test our hypothesis that vegetation on areas with higher climatic variability are less prone and less sensitive to the extreme weather events due their better acclimatization. Areas with high and low meteorological variability were selected from meteorologically representative areas of the country (*Kern, 2017*). The results (presented at the 7th Advanced Training Course on Land Remote Sensing held by the European Space Agency, ESA) reveal that the response of croplands and grasslands to climate anomalies is linear, and areas with lower climatic variability show stronger response to the extreme weather events, especially in case of grasslands. The Pálfai Drought Index (PDI) was also applied to study the relationship between the strength of the droughts and the NDVI anomalies (*Kern et al., 2017e*), revealing an obvious negative relationship in case of agriculture and grasslands, while forests showed a more complex behaviour.

Studying the forest ecosystem productivity was also part of the research (*Ostrogović Sever et al., 2017*).

Summary of the scientific results

The results of the present OTKA PD project clearly showed that it is possible to detect the effects of weather and climate anomalies on the vegetation by satellite remote sensing within the Carpathian Basin. The basic questions of the planned work were answered: (1-2) the range and interannual variability of the various vegetation related indices and characteristics retrieved from the remote sensing data were determined in the Carpathian Basin; (3) their response to the variability of the weather were examined (separately for various land cover types); (4-5) the nature of changes and the magnitude of the anomalies in the state of the vegetation caused by the extreme weather conditions were studied, as well. The MODIS-based vegetation index datasets provide invaluable information about the dominant controls of plant growth. Based on the results of the project we gained new information about the state, the phenological cycle, the productivity of the vegetation and its natural or anthropogenic changes.

Summary of the publication activity

Based on the research during the 3-year project 3 peer-reviewed papers were published in English by the PI (2 is open access, 2 has Impact Factor in Q1 journals, and 2 with the PI as the first author); 2 popular scientific papers were published in Hungarian (both of them with the PI as the first author); 9 posters (6 of them with the PI as the first author) and 8 lectures (5 of them with the PI as the first author) were presented on international conferences; and 1 open access, referenced database was published with DOI number, and two additional websites were created.

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The publications of the project (which are listed without Internet links) are available at:
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