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E7 GEOINFORMATICS PROGRAM

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APPLICATION OF SATELLITE IMAGE TIME SERIES IN THE HUNGARIAN FOREST DISTURBANCE MONITORING

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1. Introduction

Forest disturbances in Hungary have become more frequent in the last decades. Climate change exacerbates both biotic and abiotic damage, thus, damage due to wind, drought, flood, insect outbreaks, viruses, and fungi has increased both in number and intensity recently. The disturbances can be monitored by satellite-based remote sensing technologies, among others.

Due to the huge importance of forests and the more and more frequent forest damage, this technology has become a real alternative to field surveys by providing data with high frequency, and accuracy, and often free of charge. Currently, imagery of several space programs is available for forest monitoring purposes. Systematic and automatized monitoring can be achieved with complex monitoring systems containing remotely sensed and ground-based datasets.

A related technology, i.e., cloud computing, provides on-demand resources and services via the internet, enabling one to run monitoring systems online without owning the information technology infrastructure and downloading and uploading large datasets, making the process faster and more flexible.

Large-scale forest monitoring systems rely on these technologies since forest stands can often be found sparsely and their dynamics can only be studied in longer term. Satellite images can be used to detect both the change in forest expansion and health state. Via photosynthetic activity, one can monitor the health state of forests, which can be described with vegetation and water indices (like Normalized

Difference Vegetation Index (NDVI) or Normalized Difference Water Index (NDWI)) derived from satellite images.

In addition to abiotic and biotic damage, anthropogenic activities can be detected on satellite images as well that affect forest attributes such as canopy closure due to clear-cuts or selective logging. These disturbances could temporarily decrease index values, thus their distinction is an important task. Artificial Intelligence (AI) built into the monitoring algorithm could help detect both natural and anthropogenic disturbances. However, remote sensing cannot reveal the reason for disturbance in the forest, but it can trigger a ground-based survey that can identify it.

Since 2017 the Hungarian Forest Research Institute operates the Hungarian Remote-sensing based Forest Health Monitoring System (in Hungarian Távérzékelésen alapuló Erdőállapot Monitoring Rendszer, shortly TEMRE) to monitor forest health about environmental changes and climate change. The system is based on filtered and forest masked Terra MODIS NDVI image composites with moderate, 250x 250 m spatial and 16 days temporal resolution. The forest state is described by NDVI Z (standardized Normalized Difference Vegetation Index), which is based on the actual, long-term (2000-2020) average and the standard deviation of forest pixel values. NDVI Z maps are regularly published and supported by tree species and site factor map layers.

Developments are needed due to the limited lifespan of satellites and the possibility of acquiring datasets of ever-increasing accuracy and consistency, thus the first goal of my PhD thesis is to develop the method further applied in TEMRE. These developments could make it possible to use high-resolution, constantly updated satellite image series supported by cloud computing, artificial intelligence, and ground-based datasets for the whole of Hungary, which is the second main goal of this PhD thesis. In the future, it would be desirable to merge this system with, and integrate it into, a new, European monitoring system.

2. Research hypotheses

1. Satellite images can be used to monitor the health state and forest expansion. The remote sensing-based forest monitoring systems are suitable detecting changes and supporting field-based monitoring. Such systems exist in Europe (Czechia, Norway, Germany) and Worldwide too (USA, Canada, Australia).
2. Forest health can be monitored in Hungary based on a 10x10 m spatial resolution Sentinel-2 L2A satellite images series in the 2017-2020 period using specific indices.
3. Cloudless annual and monthly satellite image composites can be created for the entire vegetation season (from April until November) with spatial, temporal and cloud filtering methods.
4. Interannual forest health disturbances due to biotic and abiotic damage can be detected by vegetation and water indices (Normalized Difference Vegetation Index (NDVI), NDVI change (NDVIch), Z NDVI (standardized NDVI), Normalized Difference Water Index (NDWI), Enhanced Vegetation Index (EVI)) derived from annual/monthly composites of Sentinel-2 L2A satellite images.
5. By developing a specific computer code system, a novel forest monitoring system can be created for Hungary in

the GEE cloud computing interface utilizing the above-mentioned Sentinel-2 dataset, and indices derived from it.

6. The Copernicus forest maps can support the system by providing novel, satellite-based forest masks for both the study areas and the whole of Hungary. These up-to-date masks could improve monitoring accuracy with the designation of forested areas.
7. The ground-based dataset of the National Forest Damage Registration System can be used as validation of remotely sensed data by comparing damaged forest compartments having both field reports and satellite images.

4. Methods

In this thesis forest health was studied with remote sensing methods in three selected study areas: Nagyerdő of Debrecen, Farkas-erdő of Sárvár, and Central Bükk. These areas differ in size (1092-5665-49152 ha), terrain (plain and mountainous), location (eastern, western, and northern parts of Hungary), and typical forest communities (oak with Lily of the valley (*Convallario-Quercetum roboris*), oak-hornbeam (*Querco robori-Carpinetum*), submontane beech (*Melittio-Fagetum*)) as well.

To study these sites, I applied optical satellite images provided by Sentinel-2 satellites of the European Copernicus program. These satellites are designed for monitoring the Earth’s surface from space with a high revisit time (2-5 days) and high spatial resolution (10x10 m).

Google Earth Engine (GEE) cloud-based platform was used to process Sentinel images, which is designed for geospatial, interactive, big-data processing. The multipurpose applications include surface monitoring: land cover and land-use changes, which is ideal for forest monitoring. The GEE-based program runs in the virtual cloud which does not require downloading large datasets or having a strong computing infrastructure. My program is the basis of a novel monitoring system, consisting of several methodical steps to achieve monitoring goals.

The ESA Sentinel-2 MSI L2A (surface reflectance) satellite image mosaics were queried from the GEE collection to create annual composites for the vegetation seasons of each year between 2017 and 2020. Cloud filtering and forest masking were applied on each image to filter out cloudy pixels (based on metadata and quality band) and outside the study area (i.e., Hungary and three test sites) using forest boundary polygons of the Hungarian Forest Database to include only forest-covered areas and exclude water surfaces, roads, buildings, openings, nursery gardens, game areas, and shrubbery. Similarly, the time window was defined to focus on the vegetation period (from mid-April until October) when forests actively photosynthesize.

Vegetation (VI) and water indices were calculated from the masked and filtered composites, i.e., NDVI, NDWI, and EVI for each year. Change maps were also created from state maps which were based on differences between years with subtraction and standardization, in the case of NDVI, NDVI change, and standardized NDVI (Z NDVI) respectively.

Due to the computing capacity limitations of the GEE, data aggregation (in time and space) of the VI datasets was necessary with reducers (mean, median, standard deviation), before visualization and exportation. True colour composites (RGB) were also made with a median reducer.

Using the complete NDVI time series from 2017 to 2020, charts were aggregated with a median reducer. These charts were made for the most dominant tree species and exported with the maps to Google Drive in CSV and georeferenced TIFF format in the case of images, respectively, providing the possibility of further offline analysis and more detailed image visualization.

Exported VI maps were compared to field reports on pixel-level, where forest damage was investigated from the point of view of the area (ha), frequency (0-100%), and intensity (0-100%). The damage frequency is the number of damaged given trees compared to all trees in the same species in the compartment expressed in the percentage. While the damage intensity shows the severity of damage and health deterioration compared to the healthy state, given in percentage.

5. Results and conclusions

The combined dataset of vegetation index maps derived from satellite images of the GEE-based forest damage monitoring system and the ground-based reports proved to be suitable for accurate forest health assessment.

In the **Nagyerdő of Debrecen,** the remote sensing method showed 94.3% total accuracy on pixel level when ground-based damage reports were compared to reclassified Z NDVI values. Analysis of Z NDVI maps showed that the composite of the base year 2017 had generally high Z NDVI values with healthy vegetation but areas with clearcuts and other sparsely vegetated forest compartments also appeared. In 2018 general Z NDVI decrement is detected in most of the forest due to drought and ice damage. While in 2019 and 2020 generally positive anomalies are experienced on the maps as a result of artificial plantings after clear cuts and regeneration of less forested areas. Despite the general positive changes, negative ones were also noticed, in 2020 the northeast part of the forest started to become less vital and showed lower Z NDVI values on the map, which is mostly Pedunculate oak-dominated and known for being under heat and drought stress for decades already.

Application of **Random Forest**-based (RF) machine learning method in cloud computing showed the distribution of different forest community types with 82.1% accuracy, when the remotely-sensed values were compared to forest plans including tree species data.

The composites created for the **Farkas-erdő** showed interesting results per se and in comparison, in 2017-2020. Analysing the Z NDVI maps it could be stated that in 2017 several forest compartments were spotted with lower photosynthetic activity due to ice break, but generally, the majority of the Farkas-erdő was healthy with high Z NDVI values. The damaged forest compartments showed signs of improvement in 2018 and 2019 with higher index values, however, the general state worsened in other parts due to drought. In 2019 forest damage took place again, resulting in a decline in index values. In 2020 it was still visible but with lover intensity, also new damage was observed.

In **Central Bükk**, the most severe damage was caused by snow break and windfall in April 2017, but in May and

June, the same was reported as well as in April 2018 and 2019. While drought affected Bükk in August and September 2017 and 2018, and September and October in 2019 and 2020. Spruce dieback was registered in September 2018 and June 2019.

By the GEE method, new maps were made for this area and showed partial agreement with our previous studies, the damage in 2017 was visible on these maps as well, however to a smaller extent and intensity. In the novel GEE method, 0.56% of the Central Bükk area was damaged when ZNDVI was < -0.5. It was similar to damage reports but not to our previous studies with different methods, where 1.8-2.2% damaged area was shown. The differences had several reasons the resolution of Sentinel-2 is finer than in the case of MODIS and the investigated period is only 4 years compared to the 20 years, which is important in the calculation of Z NDVI, where the long-term mean is one of the key factors.

Comparing my results to the results of previous studies, a high variety was observed, depending on the satellite types, study area and tree species. Even in Central Europe, when Sentinel-2 imagery and commonly used vegetation indices were applied for stands with similar site conditions, moderate results (R^2=0.5-0.6) were reported from German, Polish, Czech, Slovak, etc. studies surveying forest damage.

6. Research thesis

1. Forest health state was successfully monitored based on high resolution, annual Sentinel-2 satellite image series

from 2017 until 2020 in the selected study areas (Nagyerdő, Farkas-erdő, Central-Bükk) in Hungary, using Google Earth Engine online, cloud computing system. The study sites differed in location (east, west, and north), terrain (plain, mountainous), size (1092-5665-49152 ha), and species composition (oak, hornbeam, beech–dominated forests) to represent different forest site types.

2. Forest damage was shown on vegetation and water index maps (NDVI, Z NDVI, NDWI, EVI) and charts derived from nearly cloudless, Sentinel-2 composites of the entire vegetation season (April - October). Both abiotic (wind, snow, ice, drought) and biotic (dieback, insects) damage resulted in negative changes in the index values. In the case of Z NDVI, the threshold of -0.5 was chosen for forest damage, where all equal or lower values refer to negative change, while the ground-based damage ratio was set at least 30%.

3. Remotely sensed forest damage was validated with systematically collected ground-surveyed forest damage reports based on the damaged area, intensity, frequency, and sanitary logging data. The index values derived from satellite images were compared to these parameters. The ratio was a novel field surveyed data type which was based on the damage and total area of the compartments. All study sites' mean total accuracy values showed that frequency has the highest accuracy at 78%, followed by the ratio at 46% and intensity at 30%. Regarding each study site, Nagyerdő showed 94% total accuracy in the surveyed four years, while Farkas-erdő did 80% and Central Bükk 61%.

4. The Google Earth Engine-based method for forest health assessment is capable of running a nationwide monitoring system. The Sentinel-2-based method was successfully tested for Hungary on the country level with Copernicus forest cover maps. The satellite-based forest cover maps were generally more up-to-date but larger in extension with 1-20% in the mean for the study areas and country-wide scale compared to the land-use-based Copernicus maps of the National Forest Database or National Ecosystem map. The reason behind it is, that they are all based on different methods, have different formats (vector vs raster, 10x10 vs 20x20 m resolution) and made in different years. The definition of forest and forest masking technique is not the same either.
5. Machine Learning can be applied for forest species classification in the GEE system. Species composition can be mapped on pixel level using Random Forest method on Sentinel-2 composites and validated by ground-based datasets. In the case of Nagyerdő 82% Total Accuracy was achieved for the four dominant tree species (pedunculate oak, red oak, Scots pine and Black locust).
6. The novel approach could be integrated into the operating TEMRE system or the Forestry Subsystem of the Hungarian Earth Observation Information System since both utilize S-2 imagery.

7. Publications

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