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Monitoring forest response using Sentinel-2 observations to climatic factors along the Carpathian Mountains

KEYWORDS: Sentinel-2 time-series, forest canopy, precipitation, temperature, lagging effects

Introduction

Vegetation is often seen as a biological indicator of climate change. Although various factors such as temperature, water, light and nutrients influence vegetation dynamics and affect plant physiology, phenology, growth rates and water availability, the study of the direct and indirect effects of climatic conditions on vegetation development is complex (Mehmood, 2024). Forests disturbed by climate-related changes or disturbances, such as drought and frost-related stress, affect the susceptibility of trees to pests and diseases and also influence species competition and their adaptive strategies – processes that are essential for effective understanding and management of ecosystems (Čater, 2024; Adamič, 2023).

Satellite-based vegetation observation enables continuous monitoring of forest dynamics, ecosystem transitions and changes in composition. By analysing long-term satellite data together with climate variables, we can gain valuable insights into spatio-temporal vegetation patterns and their relationship to climate factors (Mehmood, 2024).

In this study, we examine the Sentinel-2 satellite vegetation indicators to observe satellite signal responses from eight selected observation plots along the Carpathian Mountains gradient for similarities and differences. We compare the satellite-based vegetation responses using six vegetation indicators (NDVI, S2REP, kNDVI, EVI, MSAVI, NDWI) from 2017 to 2022 with meteorological data on precipitation and temperature, paying particular attention to possible time-delayed effects in the observed Sentinel-2 time series.

Material and methods

Study area. The Carpathian Mountains sweep in a wide, crescent-shaped arc about 1,450 kilometers in a north-south direction, have a difference of almost 300 kilometers between their western and eastern stretch and cover about 200,000 square kilometers. The Carpathians are geologically diverse in their vast area and consist of several mountain ranges with different relief forms and include several different ecosystems such as mixed forests, alpine meadows

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and wetlands. The climate in the Carpathians is diverse and is characterised by cool, humid conditions in the higher altitudes and a warmer, continental climate in the foothills, which contributes to the rich biodiversity and pronounced seasonal variations in the region. Precipitation patterns and mean annual and monthly air temperatures vary mainly according to altitude above sea level, but not to the same extent and patterns (Kondracki, 2024).

The study analyzed eight forest sites, distributed along the Carpathian arc. These sites are permanent research plots, situated at elevations between 820 and 1038 meters above sea level, consisted of mature beech and fir trees (Čater et al., 2024). Two sites are old-grown reserves (Zagon and Salajka), while the other sites are considered managed forests (Figure 1).

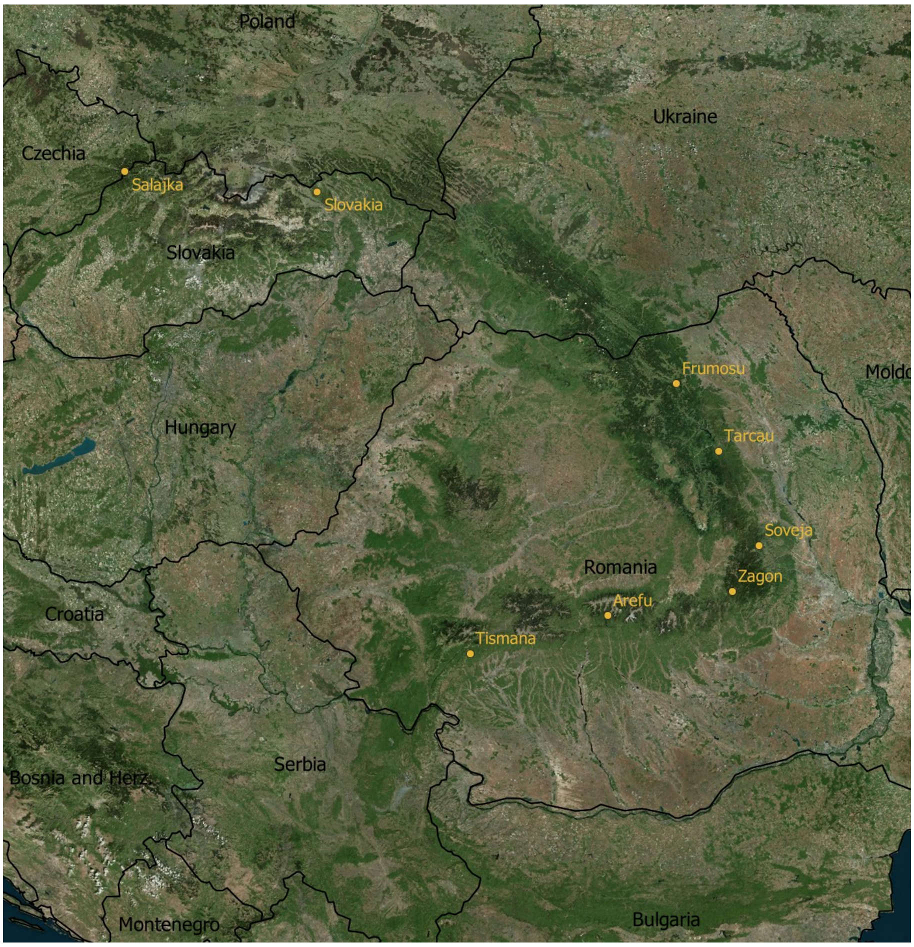

Fig. 1. Location of research sites. Eight sites (shown in yellow color) with mature fir–beech forest stands at an altitude between 820 and 1038 m above sea level were selected and analysed along the Carpathian Mountains at a north-south distance of more than 1500 km and an east-west distance of 300 km. The southern locations, Tismana, Arefu and Zagon, are situated at higher altitudes. Bing aerial imagery in the background.

Satellite-based vegetation indicators. Sentinel-2 time series for six vegetation indicators (NDVI – Normalised Difference Vegetation Index, S2REP – Sentinel-2 Red Edge Position, kNDVI – kernel NDVI, EVI – Enhanced Vegetation Index, MSAVI – Modified Soil Adjusted VI, NDWI – Normalised Difference Water Index) from 2017 to 2022 were created for each observation site with surroundings. The preparation included the elimination of clouds, shadows and non-valid observations using the s2cloudless algorithm. The data sets were also smoothed using the Savitzky-Golay temporal filter to reduce noise while preserving the satellite signal trend.

Sentinel-2 spectral bands have spatial resolution of 10, 20 and 60 m, time series were prepared in 10 m resolution, and have a revisit frequency of 5 days at the Equator.

Meteo datasets. Daily gridded meteorological temperature and precipitation data from Copernicus E-OBS were used. The time series were processed at a spatial resolution of 1 km (Harris, 2020). Different time intervals for precipitation summaries and temperature averages were used in the analyses.

Time-lagging analyses. Time-delayed effects occur when an event at one point in time impacts a variable of interest later (Nicolau, 2024). For example, persistent drought in spring or heavy rain during the flowering period can severely affect tree development in later stages or influence their condition in the next season. While seasonal comparisons reveal trend development, understanding forest responses through satellite observations requires exploring how precipitation and temperature influence seasonal forest growth and how these patterns appear in satellite vegetation indicators.

In the study, we focused on the spatio-temporal dynamics of various vegetation indicators. NDVI, kNDVI, EVI and S2REP are indicators of vegetation vigour, condition and chlorophyll content. They were selected because they consist of the inclusion of different spectral bands so that the variability of response in different spectral regions can be observed (Govender, 2009). MSAVI is an alternative to assess the state of vegetation when the soil surface is not completely covered with vegetation. NDWI is used to monitor changes in water content and estimates the amount of moisture in the vegetation, which is used to monitor changes in water content in the leaves.

The research methodology involves the analysis of satellite imagery and meteorological datasets to investigate the interactions between selected vegetation indicators (VIs), total precipitation (P) and temperature (T). We created several time-lagged collections, where different time periods of the meteorological summaries are taken prior to the date of satellite acquisition. The previous P and T values (*lag*) that are within a certain time difference (in days, $t - lag$) from each VI (in time t), were linked to the current VI value and correlation coefficients were calculated. To assess the possibility that perhaps precipitation in the month(s) prior to the observed VI is relevant, we introduce further lagged periods in the interpretation of the vegetation response observed in the VI time series by introducing progressively longer lags back up to 200 days.

Since the meteorological datasets are available at a raw resolution of 1 km, we have also investigated the strength of these relationships using the different extent areas around the site in the VIs time series averages, i.e. 30, 50, 100, 210, 250 and 1010 m^2 respectively. Higher positive values indicate higher correlation between the elements of the dataset, and lower negative values indicate the opposite.
The aim of this approach was:

- to value seasonal forest stand satellite based observation with regard to meteorological parameters and geographical location,
- to explore the potential of Sentinel-2 data to detect spatio-temporal differences in forest response between site locations and tree species.

Results

Comparison of annual VIs time series, monthly precipitation summaries and temperature for each study site revealed years or locations with some deviations (Figure 2).

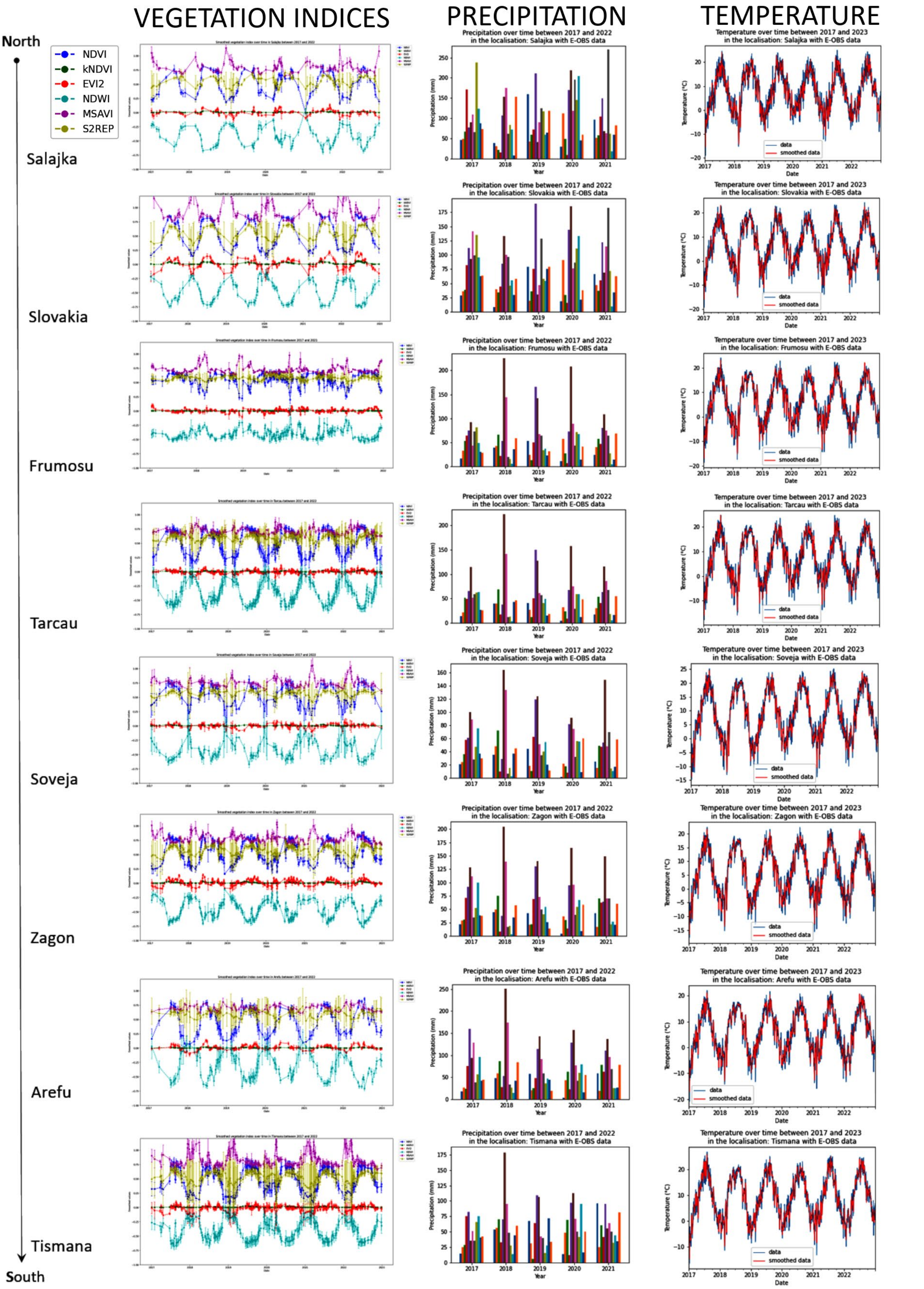

Fig. 2. Sentinel-2 vegetation indices (VIs) time series, precipitation (P) and temperature (T) regime obtained with Copernicus E-OBS meteorological data at research sites for the period 2017 – 2022 in columns. Research sites locations from north to south are presented in rows.

The year with the highest summer precipitation and lower average temperatures is 2018; this observation is slightly less pronounced for the two northernmost locations, Salajka and Slovakia. Different amounts and seasonal precipitation regimes are expressed between the research sites, decreasing slightly towards the south and also over time until 2021.

The preprocessing of Sentinel-2 time series reduced the frequency or density of vegetation indices to some degree. On average half of satellite observations are eliminated due to cloud and cloud shadow masking and limiting the time-series to vegetation season between April to November. The density of valid observations for selected study sites varies between sites and years, but likely as there is no association between precipitation amount and VI density (see year 2017 for Arefu and Tismana compared to other years).

There is a different response in vegetation indicators between sites. Larger differences are observed for MSAVI and NDWI, while the vegetation condition-orientated NDVI and kNDVI are more stable and comparable across the seasons.

Direct correlations between VIs and precipitation and temperature were rather insignificant to allow a meaningful interpretation of forest response. Nevertheless, stronger correlations between VIs and temperature and weaker correlations between VIs and precipitation were generally observed. There are no significant differences in these correlations (sign and strength) between the eight locations observed (Figure 3).

Temperature/VI	NDVI	kNDVI	EVI2	NDWI	MSAVI	S2REP
Salajka	0.57	0.47	-0.20	-0.50	-0.51	0.66
Slovakia	0.73	0.72	0.33	-0.73	-0.43	0.71
Frumosu	0.37	0.55	-0.65	-0.27	-0.36	0.43
Tarcau	0.63	0.58	-0.12	-0.63	0.07	0.53
Soveja	0.65	0.67	-0.29	-0.61	-0.12	0.64
Zagon	0.71	0.68	0.22	-0.66	-0.43	0.67
Arefu	0.64	0.59	0.17	-0.58	0.09	0.38
Tismana	0.75	0.74	0.11	-0.69	-0.43	0.73

Precipitation/VI	NDVI	kNDVI	EVI2	NDWI	MSAVI	S2REP
Salajka	0.18	0.06	0.10	-0.07	-0.07	0.19
Slovakia	0.37	0.33	0.03	-0.35	-0.26	0.30
Frumosu	0.10	0.41	-0.46	-0.04	0.04	0.15
Tarcau	0.41	0.43	0.14	-0.38	0.18	0.17
Soveja	0.20	0.35	-0.11	-0.16	0.01	0.26
Zagon	0.26	0.36	0.05	-0.22	-0.02	0.13
Arefu	0.43	0.61	0.55	-0.47	0.59	-0.15
Tismana	0.19	0.28	0.19	-0.18	0.13	0.07

Positive corr.]0.5, 1] Negative corr. [-1, -0.5[No significant corr.]0, 0.5] [-0.5, 0[

Fig. 3. Correlation coefficients between vegetation indices and temperature and precipitation during the growing season. The monthly precipitation total, the monthly mean temperature and the monthly mean vegetation index were used to calculate the correlation, taking into account the period from April to November.

T and VIs: A strong positive correlation was found for NDVI, kNDVI, S2REP, indicating that these VIs tend to increase with increasing T, suggesting that temperature influences the improvement of forest health, greenness, vigour and clorophyll. For NDWI, there is a strong negative correlation, suggesting that NDWI decreases with increasing T, which is due to decreased water availability and increased evapotranspiration. For MSAVI and EVI2, the correlation signs are mixed and less significant.

P and VIs: A mostly weak positive correlation was found for NDVI, kNDVI and S2REP, indicating that a higher P value generally leads to a higher VI value and thus to an improvement in the health and greenness of the forest. For NDWI, there is a moderately negative correlation, suggesting that NDWI decreases rather unusually with increasing P value, indicating that the water cycle of a forest is a complex system. For MSAVI, EVI2, similar to T, the correlation signs are mixed and less significant.

The inclusion of different intervals of previous precipitation summaries and temperature average in correlation analyses with VIs revealed several interesting relationships. To illustrate this on temperature examination, for each data set for which we know the value of the vegetation indices, we take the temperature on the same day and calculate the correlation and the average temperature on the same day + 9 days before (i.e. a total of a 10-day window) and then the same for 20, 30, 40... and 90 days and calculate the correlations. The results for the previous temperature conditions (Table 1) indicate that the NDVI correlates strongly positively and EVI2 strongly negatively with previous temperature conditions of up to one month. Shorter previous temperature conditions of one to three weeks seem to correlate well with the NDWI. For other VIs, a greater diversity is observed and the correlations are weaker.

Table 1. Maximum correlation and associated prior temporal window size in days between temperature and VIs for each index and location.

Site location	NDVI		kNDVI		EVI2		S2REP		MSAVI		NDWI	
	Corr.	Days	Corr.	Days	Corr.	Days	Corr.	Days	Corr.	Days	Corr.	Days
Salajka	0.88	24	0.78	40	-0.82	24	0.47	31	-0.66	7	0.74	15
Slovakia	0.93	29	0.90	51	-0.91	29	0.77	16	-0.78	16	0.79	20
Frumosu	0.67	1	0.68	90	-0.60	1	-0.34	22	-0.62	2	0.79	20
Tarcau	0.88	17	0.56	90	-0.86	7	0.38	20	-0.41	90	0.73	6
Soveja	0.86	31	0.62	90	-0.82	17	0.20	66	-0.40	90	0.77	6
Zagon	0.90	27	0.77	71	-0.88	27	0.68	48	-0.59	90	0.77	16
Arefu	0.88	9	0.61	90	-0.84	8	0.63	16	-0.39	90	0.74	8
Tismana	0.91	27	0.80	53	-0.87	10	0.65	48	-0.65	84	0.80	14

Various intervals of previous precipitation summaries in correlation analyses with VIs are shown in Figure 4. For NDVI, kNDVI and S2REP, the correlation increases with the size of the time window, consistently in all cases and at all locations. This suggests that moisture conditions up to three months in the past may have an influence on the state of the vegetation canopy condition as was observed for these satellite vegetation indicators. EVI also follows this correlation dynamic, but less consistently and also varies between sites. NDWI and MSAVI seem to have an opposite relationship. Both show a negative correlation with increasing strength up to a period of three months or even longer, and are moderately consistent at all sites.

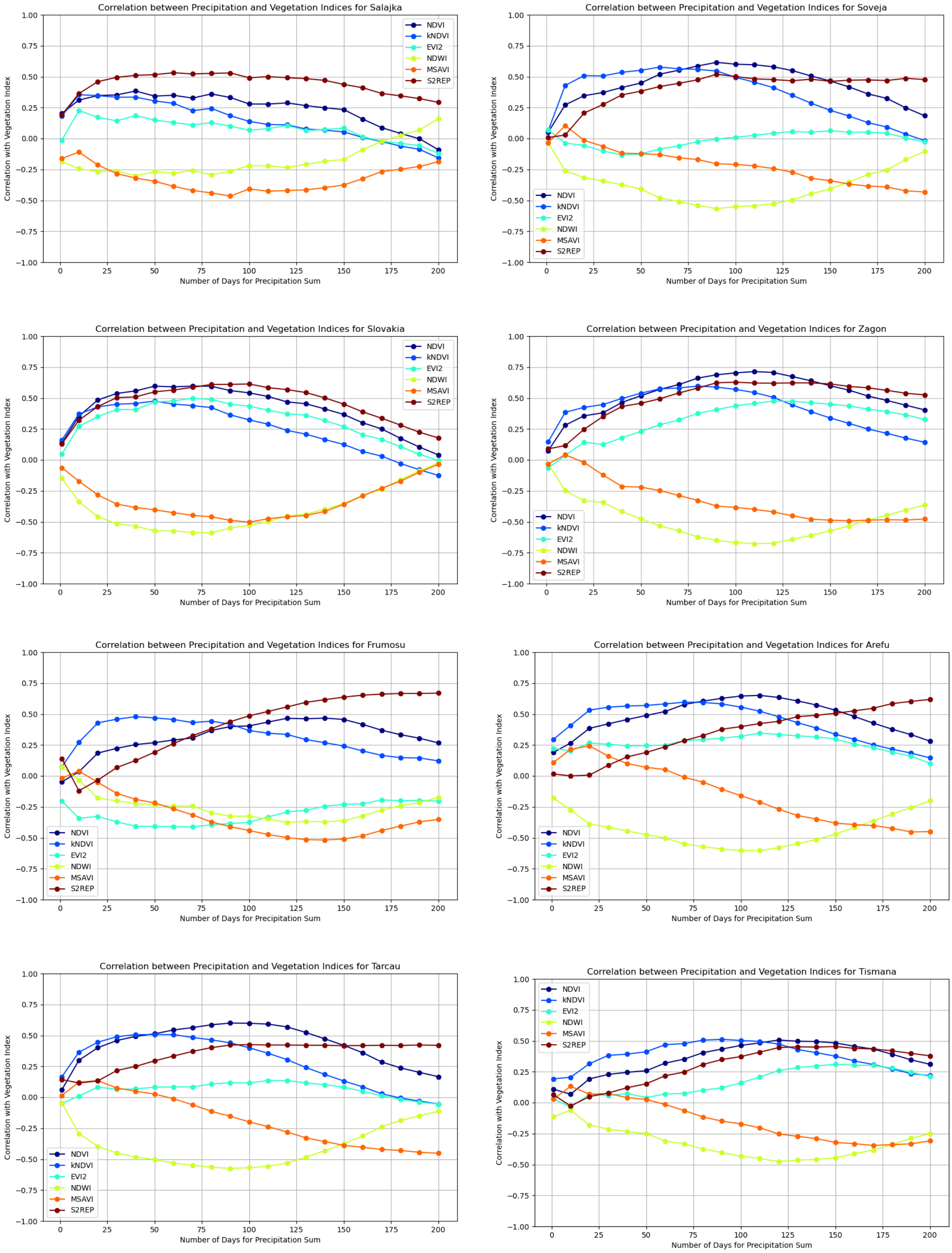

Fig. 4. Correlation (vertically) and associated size of the previous time window in days (horizontally) between the precipitation summary and the VIs for each index (colored lines). Eight charts represent eight study locations from north to south, continuing in two columns.

Since the spatial resolution of the meteorological data is rather coarse (1 km) and the satellite vegetation indicators have a resolution of 10 m, we were also interested in how the size of the area influences these correlations. The larger the area, the greater the mix of tree species and forest stand structures is averaged into correlation analyses. In general, the correlations between precipitation and VIs were lowest at larger extents of 1 km^2. This was true for the NDVI for most locations except Frumosu, Soveja and Tismana. We had expected the correlations to be more pronounced for smaller areas where forest cover is more homogeneous, but the results are not clearly substantiated and consistent between locations.

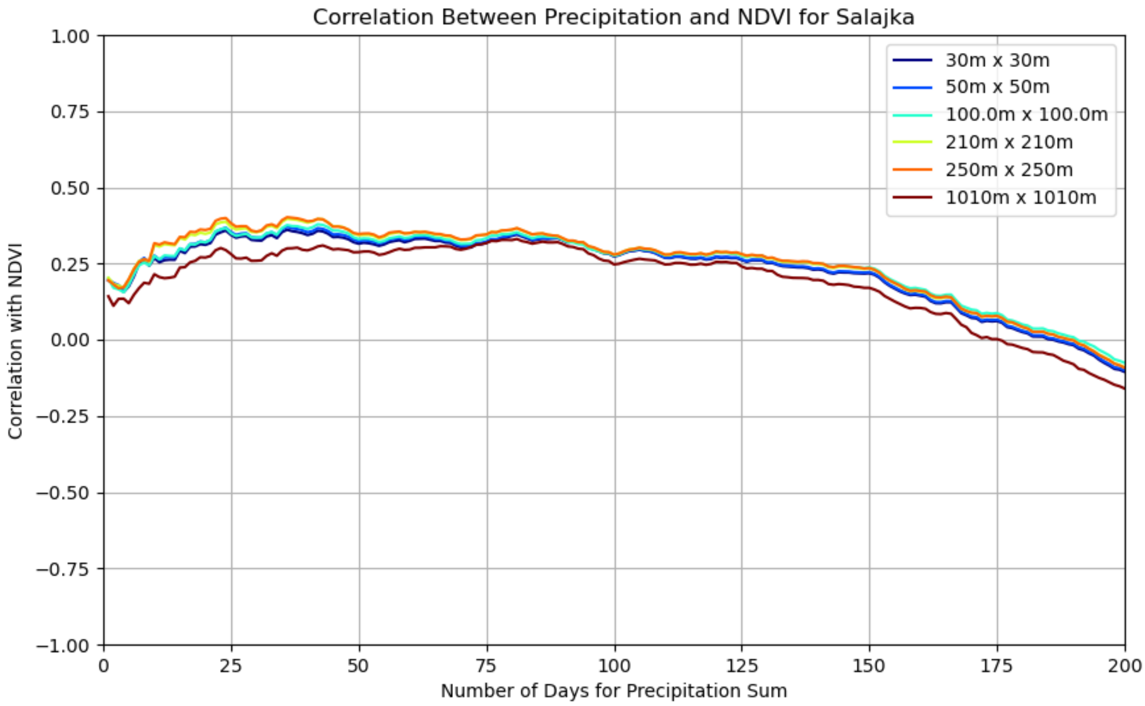

Fig. 5 Study of different area sizes in precipitation and VI correlation analysis. The example is shown for the Salajka site and the previous moisture condition on canopy response in the NDVI development.

Conclusion

Understanding the intricate relationship between climate variables and satellite-derived vegetation indices is essential for effective ecosystem understanding and management. Our experiments were designed to address the question of whether trees as observed with satellite vegetation indicators along the Carpathian Mountains respond similarly to meteorological data. Therefore, the correlation coefficients between Sentinel-2 satellite derived vegetation indicators (VIs) and precipitation and temperature were analysed. Direct (date to date) correlations indicate that the correlation between VIs and temperature is more pronounced and that the correlation between VIs and precipitation is weak and less significant. However, since forest parameters observed using vegetation/soil/moisture indices might respond with delay to meteorological parameters, we also explored the relationship between Sentinel-2 satellite vegetation indicators and precipitation and temperature at multiple time steps using a correlation coefficients providing association strengths and tested for possible time-lagged effects. By analysing the time series lag, we found that the preceding precipitation can contribute to the correlation of vegetation indicators up to three months, while the preceding average temperature contributes in a shorter time, for example for the NDVI within one month.

The interpretation of the various vegetation indicators in comparison to meteorological parameters requires further testing in which field data and phenological characteristics of the site as well as canopy structure and other environmental parameters should be examined and considered. The dependence of the satellite-derived vegetation response on meteorological factors should also be tested with other metrics and models, e.g. time-warping models, before drawing firm conclusions for locations along the Carpathian gradient.

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