

Remote sensing for forestry: assessing tree stress and climate-induced changes in the Vrsac Mountains

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Abstract

The forests of the Vrsac Mountains, located in the southeastern part of the Pannonian Plain, represent a unique ecological system within an otherwise predominantly agricultural landscape. The dominant tree species are sessile oak (*Quercus petraea* [Matt.] Liebl). Increasing climatic variability, particularly rising temperatures and prolonged drought periods, has begun to alter forest dynamics, raising concerns about their long-term resilience.

This study assesses drought-induced stress in the mixed forest ecosystems of the Vrsac Mountains using remote sensing data from the years 2023 and 2024. To evaluate the condition of forest vegetation and detect drought-induced stress, four vegetation indices were used in this study: Enhanced Vegetation Index (EVI), Triangular Vegetation Index (TVI), Moisture Stress Index (MSI), and Normalized Difference Moisture Index (NDMI). Each of these indices provides specific insights into different aspects of vegetation vitality, canopy structure, and moisture availability, making them highly suitable for use in forest environments, especially in complex and heterogeneous mixed stands.

Results indicate a dramatic increase in the percentage of forest areas affected by drought in 2024 compared to 2023. In 2024, 39.16% of the forested surface showed signs of stress according to EVI, 46.9% according to TVI, 41.57% based on MSI, and 44.2% based on NDMI. In contrast, the same indices showed minimal stress in 2023: 0.37% (EVI), 0.69% (TVI), 0.61% (MSI), and 0.6% (NDMI). The sharp contrast between the two years is attributed to significantly reduced precipitation and above-average temperatures during the summer of 2024, especially in June and July. These climatic conditions intensified water stress and contributed to canopy thinning, leaf discoloration, and chlorophyll degradation. Among the indices, TVI and NDMI proved to be the most sensitive in capturing early vegetation response to drought.

These findings underscore the growing susceptibility of forest ecosystems in the Vrsac Mountains to climate extremes. The use of vegetation indices in drought monitoring enables spatially explicit assessments of vegetation stress and can support early warning systems, forest management planning, and long-term climate adaptation strategies.

Keywords: vegetation indices, satellite images, drought, mixed stand forest, forest environments.

Introduction

Forests play a vital role in global and regional ecological stability, acting as carbon sinks, regulators of microclimates, and providers of essential ecosystem services. However, in recent decades, forest ecosystems have become increasingly vulnerable to climate-induced stressors, most notably prolonged droughts and rising temperatures. These stressors often lead to physiological decline in trees, reduced photosynthetic activity, and in severe cases, large-scale tree mortality. Understanding and detecting early signs of such stress is crucial for effective forest management, biodiversity conservation, and adaptation to climate change. Forests represent a fundamental component of terrestrial ecosystems, providing essential services such as carbon sequestration, microclimate regulation, soil stabilization, and biodiversity conservation. However, under the influence of accelerating climate change, forests are increasingly subjected to abiotic stressors—most notably prolonged droughts and extreme temperature fluctuations—which can severely impact their structure, productivity, and long-term ecological function [1,2]. In recent years, tree mortality and forest decline linked to

drought and heat stress have been observed across Europe and globally, underscoring the urgency of systematic, scalable, and timely forest monitoring solutions [3].

Remote sensing technologies, particularly those relying on multispectral satellite observations, have emerged as powerful tools for assessing forest condition across large spatial extents and with high temporal resolution. Multispectral satellite sensors, such as those onboard the Sentinel-2 constellation, offer consistent and spatially detailed measurements of reflectance in visible, near-infrared (NIR), and shortwave-infrared (SWIR) wavelengths. These bands enable the calculation of various vegetation indices (VIs) that serve as proxies for key biophysical properties of vegetation, including canopy greenness, water content, and pigment degradation [5]. The use of time-series vegetation indices allows researchers to detect changes in forest health, monitor disturbance events, and assess the effects of prolonged drought on vegetation function [3].

Studies have demonstrated that vegetation indices such as NDVI, NDMI, SAVI, and MSI are particularly effective in quantifying drought-induced stress and vegetation decline [4]. For example, a reduction in NDVI and NDMI values often corresponds to lower photosynthetic activity and decreased water availability, while increases in Land Surface Temperature (LST) signal thermal stress and potential canopy desiccation. Furthermore, spatial and temporal mapping of these indices provides actionable insights into the severity and progression of drought impacts [1].

Importantly, the integration of remote sensing data with geographic information systems (GIS) enables forest managers and researchers to detect early warning signs of decline, identify vulnerable hotspots, and evaluate long-term trends in ecosystem resilience [5,2]. Tools such as the European Forest Condition Monitor (EFCM) exemplify the practical application of satellite-derived indices for identifying regions of anomalous forest greenness and vitality [2].

The intensification of droughts across Europe in recent decades has raised significant concern regarding forest ecosystem vulnerability, productivity loss, and long-term resilience. Extreme drought events, such as those in 2018, 2020, and 2022, have caused substantial forest degradation, ranging from premature discoloration and defoliation to widespread canopy dieback and tree mortality [6,7,8]. These impacts have been particularly pronounced in temperate deciduous and mixed forests, where prolonged water deficits impair photosynthetic capacity, disrupt metabolic processes, and compromise ecosystem services.

Remote sensing technologies, especially multispectral satellite-based platforms such as Sentinel-2—have become essential tools for monitoring forest conditions in the context of climate-induced stress. Satellite-derived vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Moisture Stress Index (MSI), and newer chlorophyll-sensitive indices (e.g., CCI, CIRE) offer scalable, repeatable, and objective means of assessing vegetation health across diverse landscapes [5,9]. Time-series analyses of these indices enable the identification of trends in greenness, canopy water content, and pigment degradation, which are all key indicators of drought stress and recovery potential [4,6].

Recent studies have demonstrated the value of combining vegetation indices within situ measurements (e.g., tree water deficit, soil moisture) to validate satellite observations and improve the detection of stress responses at species and stand levels [9,10]. Likewise, integrating defoliation and discoloration as co-occurring symptoms in multispectral regression models has proven effective in quantifying forest health beyond traditional greenness-based approaches [8]. Additionally, the European Forest Condition Monitor and similar frameworks use vegetation index anomalies to flag areas of unusual forest decline, supporting early warning systems and forest management planning [2].

In Central Europe, high-resolution satellite time series have enabled the tracking of canopy disturbance with increasing temporal and spatial precision. This has revealed how drought responses are influenced by site characteristics such as slope, elevation, species composition, and soil properties, which modulate forest resistance and recovery [6,10]. As drought events become more frequent and spatially variable, near real-time monitoring using vegetation indices emerge as a critical approach for adaptive forest management [3,9].

Forest ecosystems across Europe are increasingly exposed to a range of abiotic stressors, including drought, storms, and heatwaves, driven by accelerating climate change. These events, particularly droughts, have intensified in frequency and severity over the past decades, resulting in widespread degradation of forest structure, function, and resilience [11,12]. Excess tree mortality, canopy defoliation, premature discoloration, and long-term loss of biomass are commonly observed consequences, with over 500,000 hectares of excess mortality attributed to drought alone between 1987 and 2016 in Europe [11]. Importantly, drought-related forest mortality exhibits threshold behavior, with rapid increases once water availability drops below critical climatic baselines.

While storms and fires have also been recognized as major disturbance agents [13], the long-term and spatially pervasive nature of drought makes it a particularly challenging phenomenon to monitor. At the

same time, the ecological consequences of drought manifest across multiple scales—from physiological responses in individual trees to structural shifts at the stand and landscape level [12]. Understanding these multiscale dynamics is essential for effective forest management, especially in regions where forest composition and site-specific conditions modulate drought sensitivity.

Remote sensing has emerged as a powerful tool for monitoring forest conditions in the face of these challenges. High-resolution multispectral satellite imagery, particularly from the Sentinel-2 mission, enables the generation of vegetation indices that serve as proxies for canopy greenness, water content, and structural complexity. Indices such as NDVI, NDWI, NDMI, and MSI have been widely applied to detect drought-related stress symptoms in both coniferous and broadleaf forests [6,9,14]. More advanced indices such as the Chlorophyll Carotenoid Index (CCI), Chlorophyll Red Edge (CIRE), and Enhanced Vegetation Index (EVI) provide further sensitivity to pigment degradation and early stress detection.

Integrating these indices with time-series analysis and in situ validation has led to significant advances in near real-time monitoring of forest stress [3,9]. Furthermore, emerging methods such as combining discoloration and defoliation into unified indicators have shown improved correlation with ground-based damage assessments, enabling species-independent evaluations of forest health [8]. Still, interpretation of spectral responses requires accounting for stand properties, site conditions, and canopy architecture, which influence reflectance patterns in complex ways [15].

The difficulty in capturing degradation—defined as persistent structural and functional decline without complete forest loss—also remains a significant challenge in remote sensing [14]. Degradation signatures vary by disturbance type (e.g., drought, selective logging, fire) and require adapted spectral-temporal analysis strategies.

Recent national studies have further emphasized the vulnerability of Serbian forests, particularly pedunculate oak (*Quercus robur*), to drought stress.[16] demonstrated that trees growing at sites with deeper groundwater levels exhibited reduced pre-dawn water potential and increased antioxidant activity, suggesting stronger physiological stress responses and site-specific drought adaptation. Their findings highlight the importance of local hydrological conditions and antioxidant defense mechanisms in intra-species drought resistance. In parallel, breeding-oriented research by [17] revealed that leaf stomatal density (SD) and leaf dry mass per unit area (LMA) are key morphological and anatomical traits associated with improved intrinsic water-use efficiency (WUEi) in *Q. robur*. These traits showed strong correlations with WUEi under moderate drought conditions, providing a valuable framework for selecting drought-resilient genotypes for future reforestation and afforestation programs. Complementary evidence from an urban context was presented by [18], who reported that *Q. robur* and *Carpinus betulus* saplings subjected to water stress in non-irrigated areas of Novi Sad exhibited significantly altered stomatal conductance and increased biochemical stress markers, including elevated free proline and antioxidant activity. These physiological shifts reinforce the role of irrigation in enhancing tree resilience to urban drought conditions. Moreover, [19] provided a comprehensive assessment of climate change impacts across Serbian forest ecosystems, documenting a mean temperature increase of over 1°C from 1990 to 2019 compared to the previous climate period (1961–1990), along with regional disparities in precipitation trends. These climatic shifts have contributed to forest decline, altered species composition, and increased vulnerability to pests and diseases, particularly in the northern and eastern forest regions where drought effects are more pronounced. Species-level analyses have shown that Turkey oak (*Quercus cerris* L.) exhibits greater drought tolerance than pedunculate oak (*Quercus robur* L.), as reflected by less negative $\delta^{13}\text{C}$ values and more stable intrinsic water-use efficiency (iWUE) under dry conditions. These findings suggest that *Q. cerris* may serve as a more reliable bioindicator of climate variation and drought severity in lowland mixed forests of northern Serbia [20]. Furthermore, drought-induced responses have not been limited to deciduous broadleaf species. In high-altitude coniferous stands, Norway spruce forests within Kopaonik National Park have experienced extensive canopy dieback, particularly during and after the 2011–2012 drought, with bark beetle outbreaks further exacerbating the decline. Remote sensing analyses using Landsat and Sentinel-2 data confirmed that vegetation indices can effectively quantify forest cover loss and detect early stress symptoms in coniferous forests [21].

Drought stress is among the most significant challenges affecting the forests of the Vrsac Mountains. Water deficit influences tree growth by reducing photosynthetic activity, limiting nutrient uptake, and increasing vulnerability to secondary stressors such as pest infestations and fungal pathogens. In particular, sessile oak, which dominates many of the forest stands, exhibits reduced radial growth during drought years, as evidenced by dendrochronological studies conducted in the region [23]. European beech, typically confined to moist and shaded slopes, have shown increased signs of decline, with higher rates of leaf shedding, crown dieback, and mortality in particularly dry years [24,25]. In contrast, Turkey oak and hornbeam, species known for their greater drought tolerance, appear to exhibit a competitive advantage under prolonged arid conditions [26].

The consequences of these climatic shifts are reflected in the composition and structure of the forest stands. Observations in permanent monitoring plots indicate a gradual shift in species dominance, with a decline in beech populations and a relative increase in oak and hornbeam cover. Furthermore, an increase in the presence of xerophytic shrub species in the understory suggests an ongoing transition toward a more drought-adapted forest community. While the natural regeneration of key species remains evident, the success rate of seedlings, particularly beech, is significantly reduced in years with below-average precipitation. These patterns indicate that recruitment dynamics are increasingly influenced by climatic factors, raising concerns about the long-term sustainability of certain tree populations [28].

Apart from the direct physiological stress imposed on trees, drought conditions have also amplified the impact of biotic disturbances. The gypsy moth (*Lymantria dispar*), a known defoliator of oak forests, has exhibited increased population outbreaks in recent years, particularly following consecutive dry summers. Similarly, bark beetle (*Ips typographus*) activity has intensified in mixed beech stands weakened by water deficit. Such interactions between climatic stress and biotic pressures create a feedback loop, further accelerating forest decline in vulnerable areas [32,33].

Changes in soil properties further compound the effects of drought on forest resilience. Reduced soil moisture content limits nutrient availability, particularly nitrogen and phosphorus, essential for tree growth. In addition, increased surface runoff and soil erosion have been observed on steeper slopes, particularly following heavy rainfall events that occur after prolonged dry periods. These processes contribute to a decline in site quality, which in turn affects the overall health and productivity of forest stands [34,35,36].

Meteorological data from the past several decades indicate that the frequency and intensity of droughts are expected to increase in the coming years. Prolonged dry periods will likely exert selective pressure on tree populations, favoring more drought-tolerant species while leading to the decline of moisture-dependent ones. Such shifts in species composition have the potential to alter the functional role of these forests, impacting their ability to regulate microclimate, store carbon, and support biodiversity [37,38,39].

The current trends observed in the forests of the Vrsac Mountains suggest that climate-induced changes are already affecting forest structure and function. Long-term monitoring of tree growth, regeneration success, and species interactions is essential for assessing the ongoing impacts of drought and other weather extremes. While the resilience of these forests is evident in their ability to withstand episodic stress events, the cumulative effects of prolonged droughts, in combination with other disturbances, may gradually shift the ecological balance of the region's forest ecosystems. Understanding the mechanisms that drive these changes remains crucial for predicting future forest dynamics and ensuring the persistence of these valuable forested landscapes [40,41,42,43].

The increasing availability of high-resolution multispectral satellite imagery has significantly improved the capacity to monitor forest ecosystems over large spatial and temporal scales [44]. Remote sensing technologies, particularly those involving spaceborne platforms, offer a non-invasive and cost-effective method for assessing the health, structure, and dynamics of vegetation [45]. Unlike field surveys, which are often limited in scope and frequency, satellite observations enable continuous and repeatable measurements of forest conditions, making them particularly suitable for tracking seasonal and interannual changes [46,47].

Multispectral sensors, such as those aboard the Sentinel-2 satellites of the European Copernicus Programme, are capable of capturing reflectance in visible, near-infrared (NIR), and shortwave infrared (SWIR) wavelengths. These spectral bands are specifically chosen for their sensitivity to biophysical and biochemical properties of vegetation, including chlorophyll content, water status, and canopy structure [48]. By calculating spectral vegetation indices from multispectral data, researchers can derive reliable proxies for photosynthetic activity, moisture stress, and pigment degradation—key indicators of forest health [49].

Such indices allow for early detection of stress symptoms that may not yet be visible to the naked eye, providing valuable lead time for ecological assessments and management interventions. Moreover, the spatially explicit nature of satellite data enables the identification of stress patterns and degradation hotspots across heterogeneous forest landscapes. As a result, multispectral satellite monitoring has become an essential tool in modern forestry, supporting applications ranging from drought impact assessment and pest outbreak detection to carbon accounting and biodiversity monitoring.

In this study, Sentinel-2 multispectral data were applied and a suite of vegetation indices to assess the impact of drought on forest vegetation in the Vrsac Mountains (Vrsacke planine) in Serbia. By comparing imagery from the summer periods of 2023 and 2024, the study aims to detect spatially explicit changes in vegetation health and quantify the extent of drought-induced stress in a forest system that is ecologically valuable yet increasingly vulnerable to hydrometeorological extremes. This research contributes to the broader understanding of how temperate forests respond to climate variability and highlights the value of remote sensing techniques in environmental monitoring and sustainable forest management.

Materials and Methods

The Vrsac Mountains (*Vrsačke planine*) are a small, isolated mountain range located in the northeastern part of Serbia, within the province of Vojvodina. Geographically, the range is situated near the town of Vrsac, along the border with Romania, and represents one of the few orographic features within the predominantly flat Pannonian Plain. The mountains extend over an area of approximately 170 square kilometers and reach their highest point at Guduricki vrh, which rises to 641 meters above sea level, making it the highest peak in the province of Vojvodina.

The Vrsac Mountains are primarily composed of Paleozoic and Mesozoic geological formations, including metamorphic rocks such as schist and gneiss, as well as sandstone and quartzite. The geomorphological landscape is characterized by gentle ridges, forested slopes, and a mosaic of valleys and plateaus. Due to their elevation and orographic position, the mountains form a natural ecological island that contrasts sharply with the surrounding lowland agricultural terrain.

Ecologically, the area is known for its high biodiversity and relatively well-preserved deciduous forests. The dominant forest types include sessile oak (*Quercus petraea*), European beech (*Fagus sylvatica*), common hornbeam (*Carpinus betulus*), and small-leaved linden (*Tilia cordata*). These communities support a variety of flora and fauna, some of which are rare or locally endemic. The Vrsac Mountains have been partially designated as a protected landscape and are included in Serbia's network of ecologically important areas.

The climate of the region is classified as moderately continental, with pronounced seasonal variation. Winters are cold and can include snowfall, while summers are typically warm to hot, with average July temperatures ranging between 21–24°C. Annual precipitation averages between 600 and 750 mm, although interannual variability is significant. In recent years, the area has experienced an increased frequency of summer droughts, contributing to vegetation stress and forest decline. The combination of shallow mountain soils and exposure to wind and sun increases the susceptibility of forest stands to hydrological deficits, especially during dry periods extending from late spring to early autumn.

Due to its ecological significance, climatic vulnerability, and contrasting land cover, the Vrsac Mountains offer an ideal case study for the application of remote sensing techniques in assessing forest response to climate-induced stress.

To assess the extent of drought-related tree stress in the Vrsac Mountains between 2023 and 2024, a diverse set of vegetation indices was employed, Tab. 1. These indices were selected to capture different physiological and structural responses of forest vegetation to hydrological and climatic stress. By combining indices that reflect greenness, moisture content, and pigment degradation, it is possible to obtain a more comprehensive and spatially explicit picture of vegetation dynamics under drought conditions.

The Normalized Difference Vegetation Index (NDVI) was used as a standard baseline for monitoring overall vegetation health. It is widely recognized for its sensitivity to chlorophyll content and photosynthetic activity. However, NDVI can saturate in densely vegetated areas and may be influenced by soil reflectance. Therefore, it was supplemented by several additional indices tailored to forest conditions. The Enhanced Vegetation Index (EVI) was included to address some of NDVI's limitations. It offers improved sensitivity in high biomass areas, such as forest canopies, and is less affected by atmospheric interference and soil background. This makes EVI particularly suitable for monitoring changes in dense forest stands. Given the central role of water availability in drought stress, the Normalized Difference Moisture Index (NDMI) and the Moisture Stress Index (MSI) were used to quantify vegetation water content. NDMI leverages the contrast between near-infrared (NIR) and shortwave infrared (SWIR) reflectance to indicate the hydration level of plant tissues. A decline in NDMI values typically reflects reduced water content and the onset of stress. MSI, on the other hand, measures the ratio between SWIR and NIR bands and increases under stress, providing a complementary perspective on moisture loss. To capture changes in chlorophyll concentration and pigment degradation, several chlorophyll-sensitive indices were utilized. The Green Chlorophyll Index (GCI) and Chlorophyll Vegetation Index (CVI) both respond to variations in chlorophyll content, with CVI relying on Sentinel-2's red-edge bands for enhanced precision. These indices can detect early signs of stress before visible canopy degradation occurs. Additionally, the Triangular Vegetation Index (TVI) was used as a proxy for leaf area and pigment abundance. Its geometric formulation, incorporating green, red, and NIR bands, makes it particularly sensitive to shifts in canopy structure and color, which are typical symptoms of drought-affected trees. In areas where the canopy becomes sparse due to defoliation or dieback, the Soil Adjusted Vegetation Index (SAVI) was applied. SAVI reduces the influence of soil reflectance, ensuring a more accurate representation of vegetation cover in degraded patches. For more advanced drought detection, the Normalized Multi-band Drought Index (NMDI) was incorporated. NMDI uses multiple SWIR bands and provides improved sensitivity to severe moisture deficits compared to NDMI alone. The Atmospherically Resistant Vegetation Index (ARVI) was included as an alternative to NDVI in cases where atmospheric correction was imperfect.

ARVI minimizes the impact of atmospheric aerosols by integrating the blue band, making it a valuable backup when working with variable image quality.

Together, these indices form a robust analytical framework capable of detecting both subtle and severe forms of vegetation stress. Their combined use allows for cross-validation of results and increases the reliability of spatial assessments in complex forested environments like the Vrsac Mountains.

Table 1. Summary of vegetation indices used for forest drought stress assessment

Index Name	Abbreviation	Formula (Sentinel-2)	Purpose / What It Measures	Typical Value Ranges & Interpretation
Triangular Vegetation Index	TVI	$0.5 \times [120 \times (B08 - B04) - 200 \times (B04 - B03)]$	Indirect measure of chlorophyll content and leaf biomass	0–12 (higher = more chlorophyll); drop indicates stress
Normalized Difference Moisture Index	NDMI	$(B08 - B11) / (B08 + B11)$	Vegetation water content	> 0.4 = well hydrated; 0–0.3 = moderate stress; < 0 = drought stress
Moisture Stress Index	MSI	$B11 / B08$	Drought stress, inversely related to water content	< 1 = low stress; 1–1.5 = moderate; > 1.5 = high stress
Green Chlorophyll Index	GCI	$(B08 / B03) - 1$	Leaf chlorophyll content	> 0.5 = healthy; < 0.3 = chlorophyll loss
Chlorophyll Vegetation Index	CVI	$B07 / B05$	Chlorophyll variation using Red Edge bands	> 1.2 = normal; < 1 = potential stress
Normalized Multi-band Drought Index	NMDI	$(B08 - (B11 + B12)) / (B08 + (B11 + B12))$	Drought detection using SWIR bands	> 0.3 = moderately moist; 0–0.3 = slight stress; < 0 = high drought
Atmospherically Resistant Vegetation Index	ARVI	$(B08 - (2 \times B04 - B02)) / (B08 + (2 \times B04 - B02))$	NDVI-like index less affected by atmospheric influence	> 0.6 = healthy vegetation; 0.2–0.6 = stress; < 0.2 = degraded
Enhanced Vegetation Index	EVI	$2.5 \times (B08 - B04) / (B08 + 6 \times B04 - 7.5 \times B02 + 1)$	Sensitive to canopy, better than NDVI in dense vegetation	> 0.5 = dense vegetation; 0.2–0.5 = stressed; < 0.2 = degraded
Soil Adjusted Vegetation Index	SAVI	$((B08 - B04) / (B08 + B04 + 0.5)) \times (1 + 0.5)$	NDVI adjusted for soil influence	Similar to NDVI; more stable in sparse vegetation
Normalized Difference Vegetation Index	NDVI	$(B08 - B04) / (B08 + B04)$	General vegetation health and chlorophyll	> 0.6 = healthy; 0.2–0.5 = stressed; < 0.2 = degraded

To quantify drought-related stress in forest vegetation, a suite of spectral vegetation indices was computed from Sentinel-2 Level-2A surface reflectance imagery. The selection of indices was made to capture multiple aspects of vegetation condition, including photosynthetic activity, chlorophyll concentration, and moisture status. The indices were calculated using both general-purpose GIS software and command-line tools to ensure flexibility, repeatability, and computational efficiency.

Raster preprocessing was performed in QGIS 3.34, where cloud and shadow masking was conducted using the Scene Classification Layer (SCL) included in Sentinel-2 products. All bands were resampled to 10-meter resolution using bilinear interpolation to ensure spectral consistency across indices that combine 10 m and 20 m bands (e.g., NIR and SWIR).

The calculation of vegetation indices was implemented using the Raster Calculator in QGIS for visual testing, and `gdal_calc.py` for batch processing over multiple scenes. The GDAL scripts were executed via the OSGeo4W Shell, enabling automation of per-pixel computations across time-series datasets. Each vegetation index was expressed through its mathematical formula using reflectance values from specific Sentinel-2 bands. The formulas, required bands, functional interpretation, and value thresholds are summarized in Table 1.

Results

The results clearly demonstrate a significant interannual decline in vegetation conditions during 2024 compared to 2023, as evidenced by the consistent reduction in vegetation indices and the concurrent increase in moisture stress indicators. This trend aligns with the hypothesis that the 2024 growing season was subject to stronger climatic constraints—primarily reduced precipitation and elevated air temperatures—leading to increased vegetation stress, particularly in the late summer and autumn periods.

A comparative temporal analysis of vegetation indices between the 2023 and 2024 growing seasons reveals consistent signs of vegetation decline and increased moisture stress during 2024. Four indices were evaluated: Enhanced Vegetation Index (EVI), Triangular Vegetation Index (TVI), Moisture Stress Index (MSI), and Normalized Difference Moisture Index (NDMI). Mean values and standard deviations were calculated for corresponding phenological periods across both years.

	Mean	EVI		Mean	TVI		Mean	MSI		Mean	NDMI		
		Variance	Std.Dev.		Variance	Std.Dev.		Variance	Std.Dev.		Variance	Std.Dev.	
2023	1.5.20		14.7	23.05			0.53			0.31			
	23.	0.624	70	3.844	7	31.763	56.359	3	0.014	0.117	1	0.009	0.094
	30.6.2		12.7		20.82			0.50			0.33		
	023.	0.766	10	3.565	7	24.419	49.415	3	0.013	0.113	7	0.008	0.089
	15.7.2		0.04		22.91			0.49			0.34		
	023.	0.670	8	0.219	4	1.180	34.346	6	0.006	0.077	0	0.004	0.063
	4.8.20		0.00		20.20			0.54			0.29		
	23.	0.620	7	0.082	3	95.769	30.947	8	0.008	0.089	6	0.004	0.067
	14.8.2		0.00		18.20			0.52			0.31		
	023.	0.696	7	0.081	5	56.390	23.747	0	0.006	0.079	9	0.004	0.062
	19.8.2		0.00		19.14			0.55			0.28		
	023.	0.580	6	0.078	7	90.581	30.097	6	0.007	0.081	8	0.004	0.062
	13.9.2		0.00		17.96			0.56			0.28		
	023.	0.553	6	0.080	1	94.153	30.684	2	0.007	0.087	4	0.004	0.065
	18.9.2		0.00		17.32			0.57			0.27		
	023.	0.520	6	0.080	8	10.351	32.173	5	0.009	0.097	4	0.005	0.071
	28.9.2		0.77		16.47			0.59			0.25		
	023.	0.498	1	0.878	9	10.786	32.842	6	0.013	0.113	8	0.006	0.078
	18.10.		0.00		15.25			0.60			0.25		
	2023.	0.457	7	0.085	7	12.658	35.578	7	0.019	0.136	3	0.009	0.094
23.10.		0.00		12.75			0.71			0.17			
2023.	0.396	8	0.090	2	13.218	36.357	3	0.028	0.167	8	0.011	0.104	
2.11.2		0.00		11.18			0.83			0.10			
023.	0.359	9	0.093	6	1.385	37.213	2	0.042	0.204	5	0.014	0.117	
12.11.		0.07		10.62			0.79			0.12			
2023.	0.340	3	0.270	0	18.346	42.832	5	0.038	0.196	7	0.014	0.119	
20.4.2		6.86		24.12			0.45			0.37			
024.	0.691	8	2.621	0	13.428	36.645	9	0.005	0.072	4	0.004	0.061	
25.5.2		0.00		23.28			0.50			0.33			
024.	0.677	6	0.078	4	97.619	31.244	7	0.008	0.091	1	0.005	0.070	
19.6.2		0.00		20.37			0.57			0.27			
024.	0.595	7	0.081	0	10.339	32.155	6	0.013	0.115	5	0.007	0.081	
14.7.2		0.00		17.91			0.64			0.22			
024.	0.539	9	0.096	7	14.050	37.483	2	0.025	0.158	7	0.010	0.102	
8.8.20		0.00		16.56			0.69			0.18			
24.	0.495	9	0.094	6	13.870	37.243	8	0.029	0.171	9	0.011	0.106	
13.8.2		0.00		13.32			0.82			0.11			
024.	0.415	9	0.097	9	15.588	39.482	0	0.038	0.195	1	0.013	0.112	
2024	23.8.2		0.00	13.32			0.82			0.11			
024.	0.415	9	0.097	9	15.588	39.482	0	0.038	0.195	1	0.013	0.112	
17.9.2		0.01		10.58			0.91			0.07			
024.	0.346	7	0.132	8	26.183	51.170	0	0.086	0.294	0	0.023	0.153	
22.9.2		0.01		10.73			0.98			0.03			
024.	0.343	5	0.121	7	24.375	49.371	7	0.105	0.324	2	0.025	0.158	
27.9.2		0.01		10.52			1.01			0.01			
024.	0.342	4	0.116	7	20.759	45.562	3	0.100	0.315	6	0.023	0.150	
22.10.		0.01		11.61			0.87			0.08			
2024.	0.355	1	0.107	5	20.737	45.538	6	0.068	0.260	5	0.019	0.140	
										-			
6.11.2		0.01					0.95			0.04			
024.	0.318	0	0.099	9.690	1.619	40.239	7	0.057	0.238	8	0.011	0.107	

26.11.		0.00					1.12			-		
2024.	0.212	4	0.067	5.454	6.130	24.759	8	0.057	0.238	0.04	8	0.011 0.107

The analysis of vegetation indices from May to September revealed pronounced interannual differences between the 2023 and 2024 growing seasons, particularly during the peak summer months of August and September. In 2023, vegetation development progressed steadily from May, with values of the Enhanced Vegetation Index (EVI) increasing from 0.624 on 1 May to 0.696 on 14 August, indicating healthy canopy development and greening. The Triangular Vegetation Index (TVI) followed a similar trend, reaching 19.147 on 19 August. Concurrently, the Moisture Stress Index (MSI) remained relatively low, ranging between 0.520 and 0.556 in August, while the Normalized Difference Moisture Index (NDMI) maintained moderate values around 0.288–0.319, reflecting adequate canopy water content.

In 2024, however, vegetation indices showed a different trajectory. EVI peaked earlier in the season at 0.691 on 20 April and declined continuously, falling to 0.495 by 8 August and further to 0.415 on 13 and 23 August. TVI values were also lower, averaging 16.566 in early August and decreasing to 13.329 by mid- and late August. MSI, in contrast, was higher in 2024, rising to 0.820 by 13 August, suggesting elevated moisture stress. NDMI values declined substantially, from 0.189 in early August to 0.111 by mid- and late August.

During September, the differences between the two years became more pronounced. In 2023, EVI remained relatively stable at 0.553 on 13 September and 0.520 on 18 September, while TVI values remained around 17.961–17.328. MSI values increased modestly to 0.562–0.575, and NDMI values gradually decreased to 0.284–0.274.

By contrast, September 2024 was characterized by an accelerated vegetation decline. EVI dropped to 0.346 on 17 September and 0.342 on 27 September. TVI decreased further to 10.527 by the end of the month. MSI increased sharply, reaching 0.987 on 22 September and 1.013 on 27 September. NDMI declined to 0.070 on 17 September and fell even lower to 0.016 by 27 September.

When comparing average index values between the two years, the results show significant reductions in 2024:

- EVI decreased by 30.7% in August and 34.3% in September relative to 2023.
- TVI decreased by 22.9% in August and 38.5% in September.
- MSI increased by 44.8% in August and 67.8% in September.
- NDMI decreased by 54.9% in August and 85.7% in September.

These metrics indicate that vegetation growth and canopy condition peaked earlier in 2024, followed by a steeper decline during the core of the growing season compared to the previous year. While 2023 showed a gradual progression and stabilization of index values through August and early September, the 2024 season was marked by a more abrupt drop-in vegetation activity and a significant rise in stress indicators, even before the official end of the growing period.

In addition to temporal differences in vegetation index values, the spatial extent of drought impact also increased substantially in 2024 compared to 2023. The analysis of pixel-level index thresholds revealed a sharp rise in the percentage of forest area classified as drought-affected.

According to the Enhanced Vegetation Index (EVI), 39.16% of the forested area exhibited values below the defined stress threshold in 2024, compared to just 0.37% in 2023. Similarly, 46.9% of the area showed a significant reduction in TVI, in contrast to 0.69% in the previous year. The Moisture Stress Index (MSI) also indicated widespread canopy desiccation, with 41.57% of the area exceeding the stress threshold in 2024, versus 0.61% in 2023. Finally, NDMI analysis showed 44.2% of the forest surface experiencing notable moisture depletion in 2024, compared to only 0.6% in 2023.

These findings confirm that not only did index values decline in intensity, but the spatial coverage of stress also expanded dramatically. While in 2023 the drought signal was marginal and patchy, the 2024 data revealed large contiguous areas exhibiting spectral signatures of severe physiological stress.

Discussion

The interannual comparison of vegetation indices during August and September underscores a distinct pattern of drought-induced stress in 2024 relative to 2023. While both years showed typical seasonal dynamics of vegetation development, the magnitude and timing of vegetation decline were significantly altered in 2024, consistent with recent findings on the intensification of climatic stressors across European forest ecosystems [6,8,11].

In 2023, vegetation indices such as EVI and TVI indicated sustained canopy greenness and chlorophyll activity through August and into September, suggesting normal progression of phenological stages and

sufficient water availability. The steady rise in EVI from May to August, coupled with moderate MSI and stable NDMI values, points to a season with relatively favorable hydrometeorological conditions that supported forest productivity and physiological resilience. This trend aligns with the expected seasonal development in temperate mixed forests, where canopy expansion and pigment accumulation typically peak in midsummer [5].

In contrast, the vegetation trajectory in 2024 deviated sharply. EVI and TVI values declined earlier and more steeply, with EVI decreasing by over 30% in August and 34% in September compared to the same months in 2023. Similarly, TVI declined by nearly 39% in September, reflecting a reduction in both chlorophyll content and structural canopy complexity. These findings suggest that forest canopies were subject to stress much earlier in the season, likely due to prolonged drought conditions, elevated air temperatures, or cumulative water deficits—a pattern observed in recent European drought years [3,12].

Moisture-sensitive indices reinforce this interpretation. The Moisture Stress Index (MSI) increased by nearly 45% in August and nearly 68% in September 2024, indicating rising levels of canopy water stress as the season progressed. NDMI values dropped drastically—by approximately 55% in August and over 85% in September—falling to levels that signal critical vegetation desiccation and disrupted water balance. These spectral symptoms are characteristic of advanced drought response and have been linked to reduced stomatal conductance, pigment degradation, and premature senescence in deciduous forests [9,14].

Importantly, this rapid shift in vegetation conditions occurred well before the end of the vegetative season. While October and November typically mark the transition to dormancy, the observed decline in 2024 indices already reached critical thresholds in late August and early September. This early onset of physiological stress suggests that forest systems in the study area were unable to sustain typical late season functioning, highlighting a possible loss of ecological resilience under compounded drought pressure [2,13].

The homogeneity of stress responses across different index types (greenness, moisture, structural) also reflects large-scale atmospheric forcing and soil moisture depletion, as described in the literature on widespread forest decline in Central and Southeastern Europe [6]. Given that the forest stands examined in this study showed similar spectral degradation patterns regardless of exact date or subregion, it is likely that climatic extremes—rather than local disturbances—were the primary drivers of vegetation deterioration.

These findings further emphasize the value of vegetation indices derived from multispectral satellite data in monitoring climate-induced stress across broad spatial and temporal scales. In line with the European Forest Condition Monitor framework [2], the early and quantifiable decline in EVI, TVI, MSI, and NDMI in 2024 supports the implementation of real-time, index-based early warning systems for adaptive forest management. Moreover, as shown in recent studies [4,10], integrating vegetation index dynamics with ground-based indicators such as defoliation and discoloration may enhance the detection of degradation processes before irreversible forest damage occurs.

Overall, the evidence from this study supports the growing consensus that European forests are increasingly vulnerable to prolonged droughts and their cascading impacts. The significant interannual decline in vegetation indices observed between 2023 and 2024 suggests that future monitoring and management strategies must prioritize early detection, ecological forecasting, and resilience-building measures to buffer forest systems against accelerating climate change.

The substantial increase in the percentage of forested areas affected by drought in 2024 adds an important spatial dimension to the temporal vegetation decline observed in the index time series. While EVI, TVI, MSI, and NDMI values declined notably over time, the spatial analysis demonstrates that this decline was not confined to isolated pockets but rather extended across a broad portion of the forest landscape.

The sharp rise in drought-affected area—from under 1% in 2023 to over 40% in 2024 for all four indices—reflects the severity and geographic scale of the stress event. This expansion is likely linked to the combination of below-average precipitation and prolonged heatwaves during the June–July 2024 period, which coincided with key phenological stages such as canopy expansion and leaf maturation. As reported in similar regional studies [6,7], stress accumulation during these developmental windows tends to result in widespread leaf-level damage, pigment breakdown, and eventual canopy degradation.

Among the tested indices, TVI and NDMI emerged as particularly sensitive to early signs of drought stress. TVI effectively captured reductions in chlorophyll content and canopy density, while NDMI responded to progressive loss of leaf water content. These indices not only declined sharply in value but also detected stress across nearly half of the forest area, suggesting their suitability for early warning applications in operational forest monitoring.

This spatial escalation of stress exposure further validates concerns outlined in the introduction: forest ecosystems in the region are becoming increasingly vulnerable to climatic extremes, and their resilience

thresholds may be lowering over time. As indicated by [12,13], such shifts may signal long-term structural weakening, requiring adapted silvicultural strategies and drought-resilient species selection.

Ultimately, the combined temporal and spatial findings in this study underscore the need for integrated monitoring frameworks that track both the magnitude and extent of stress-related vegetation decline. The results support the deployment of satellite-based vegetation indices as cost-effective tools for identifying degradation hotspots and informing proactive forest management in the face of intensifying climate change.

Conclusion

The analysis of multispectral Sentinel-2 data revealed a pronounced decline in forest health in the Vršac Mountains during the 2024 growing season compared to 2023. Vegetation indices showed a clear shift in seasonal dynamics, with earlier peak greenness and a steeper decline during August and September 2024.

The Enhanced Vegetation Index (EVI) decreased by 30.7% in August and 34.3% in September, while the Triangular Vegetation Index (TVI) dropped by 22.9% in August and 38.5% in September, indicating reduced canopy greenness and pigment content. In parallel, Moisture Stress Index (MSI) increased by 44.8% in August and 67.8% in September, and Normalized Difference Moisture Index (NDMI) declined by 54.9% and 85.7%, respectively reflecting intensified water stress and reduced leaf moisture.

Spatial analysis further showed that the percentage of forest areas affected by drought rose dramatically in 2024, 39.16% of the area showed stress according to EVI, 46.9% according to TVI, 41.57% based on MSI, and 44.2% based on NDMI, compared to less than 1% across all indices in 2023.

These results confirm that the summer of 2024 brought early and widespread vegetation stress, significantly affecting forest conditions. The integration of vegetation indices and spatial analysis proved effective in capturing both the intensity and geographic extent of drought impact. Continued monitoring using multispectral satellite data is essential for tracking forest health and supporting timely decision-making in forest management.

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