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ARTICLE

Tourism Pressure and Vegetation Dynamics in the Carpathian Mountains

Dmytro Kasiyanchuk

Department of Geodesy and Land Management, Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska St., 76019 Ivano-Frankivsk, Ukraine

ABSTRACT

This study investigates the impact of recreational tourism on vegetation dynamics in the Carpathians, focusing on the ecological effects of infrastructure expansion and seasonal tourist flows. Analysis of NDVI trends from 2015–2025 indicates overall high vegetation productivity, but with significant localized declines. From peak years (2017, 2021, 2024) to 2025, photosynthetically active cover decreased by about 12–13% in the most affected areas. Hotspots around Hoverla, Petros, and the Bukovel corridor showed even sharper reductions of 25–35%, linked to trampling, erosion, and construction. While warmer temperatures and higher moisture generally stimulate vegetation growth, the cumulative pressure of tourism—including ski slopes, roads, and concentrated visitor traffic—drives habitat fragmentation, reduced stability of vegetation edges, and slower regeneration of alpine meadows. Areas exposed to moderate use demonstrated greater resilience, highlighting the potential of adaptive management to reconcile tourism with ecosystem health. The research integrates NDVI time-series with spatial data on tourism intensity and climate parameters, offering a comprehensive picture of vegetation changes under anthropogenic stress. Its novelty lies in directly linking ecosystem responses to quantifiable tourism indicators, providing a basis for defining ecological carrying capacity. Findings underscore the urgent need for sustainable tourism policies tailored to vulnerable zones, especially the Yaremche–Bukovel corridor. Recommendations include integrating ecosystem services into planning, setting carrying capacity thresholds, and prioritizing conservation of alpine habitats. By connecting vegetation monitoring with tourism metrics, this study establishes a framework for balancing

*CORRESPONDING AUTHOR:
Dmytro Kasiyanchuk, Department of Geodesy and Land Management, Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska St., 76019 Ivano-Frankivsk, Ukraine; Email: dima_kasiyanchuk@ukr.net

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economic benefits with the long-term ecological integrity of mountain ecosystems, positioning the Carpathians as a key case for sustainable development under rising recreational pressure.

Keywords: Recreational Tourism; Vegetation Dynamics; NDVI; Climate Change; Carpathian Region; Sustainable Management

1. Introduction

Recreational tourism in mountain regions is recognised as an important driver of socio-economic development. However, it simultaneously exerts strong pressure on natural ecosystems [1]. The Ukrainian Carpathians, one of the country's most popular tourist destinations, boast unique biodiversity and traditional land use alongside a rapidly growing leisure industry [2]. High- and mid-mountain landscapes, particularly alpine and subalpine meadows, mountain forests, and forest-meadow complexes, are highly sensitive to recreational pressure, which can result in the degradation of vegetation cover, changes in flora, and accelerated erosion [3–5]. Similar processes are observed in high-mountain lake ecosystems, where tourism exacerbates the effects of climate change [6].

Ukrainian researchers emphasise the negative impact of overgrazing, trampling, and the expansion of tourist infrastructure [7–10]. At the same time, international studies show that even moderate visitor numbers can lead to long-term alterations in vegetation structure and soil stability [11, 12]. Comparative analyses from Australia and the USA reveal varying levels of vegetation degradation depending on the recreational activity (e.g., hiking, cycling, or horse riding) [13, 14]. These findings highlight the cumulative global impact of recreational pressure.

The system of protected areas is considered vital for preserving ecosystem services in regions with intensive tourism. However, its effectiveness depends on integrating sustainable visitor management practices that take local environmental and social conditions into account [15]. Both the European Environment Agency and the Framework Convention on the Protection and Sustainable Development of the Carpathians emphasise the importance of visitor management strategies that are adapted to local contexts [16, 17]. The concepts of ecotourism and sustainable tourism are gaining prominence as potential tools for balancing conservation with economic benefits [18–22], but even 'soft' forms of tourism require careful regulation to avoid disturbing natural ecosystem dynamics [23].

Recent assessments emphasise that mountain ecosystems are particularly vulnerable to the dual pressures of climate change and tourism. The IPCC's Sixth Assessment Report (2022) [23] highlights accelerated warming, altered precipitation patterns, and increased ecosystem fragility in high-altitude regions. Studies applying remote sensing show that not only do NDVI dynamics capture the effects of climatic anomalies, they also reveal vegetation stress linked to concentrated recreational use and infrastructure development [24–26]. Furthermore, integrated approaches that combine NDVI time series with indicators of tourism intensity demonstrate how anthropogenic pressures can either amplify or offset climate-driven vegetation responses [27, 28]. These findings provide a crucial scientific basis for adaptive visitor management strategies in sensitive mountain landscapes.

Climate change exacerbates the vulnerability of alpine and subalpine ecosystems by raising temperatures, altering precipitation patterns, and increasing the frequency of extreme weather events. Combined with uneven tourist flows, these factors create patchy yet persistent zones of ecosystem instability. Remote sensing tools, including vegetation indices such as NDVI, are an effective means of identifying these zones and linking them to specific pressures.

Despite significant progress, the long-term combined effects of tourism and climate change on vegetation dynamics in the Carpathians remain insufficiently studied. Integrating data on recreational load, satellite vegetation indices, and climate parameters could provide new insights into ecosystem sustainability and inform adaptive management strategies that balance conservation priorities with socio-economic development.

2. Materials and Methods

2.1. Study Area

The research was conducted in the Ukrainian part of the Carpathian region, which forms part of the wider Carpathian Euroregion and covers an area of around 56,600 km². The territory includes the Lviv, Ivano-Frankivsk, Transcarpathian, and Chernivtsi oblasts, which are located in the west of Ukraine (**Figure 1**). The region's diverse ecosystems, ranging from lowland deciduous forests to alpine meadows above 1500 metres above sea level, are characterised by complex mountainous relief and sharp altitudinal gradients. This creates favourable conditions for recreational tourism, including hiking, skiing, spa resorts, and ecotourism. Well-known centres of intensive tourism activity include Bukovel, Dragobrat, Yaremche, and Verkhovyna. Tourism in this area has expanded rapidly over the last two decades, a period which has also seen observable climatic changes, such as rising temperatures and a shorter snow cover duration. This makes the Carpathian region a suitable case study for assessing the interaction between climatic drivers, vegetation dynamics, and tourism-related pressures.

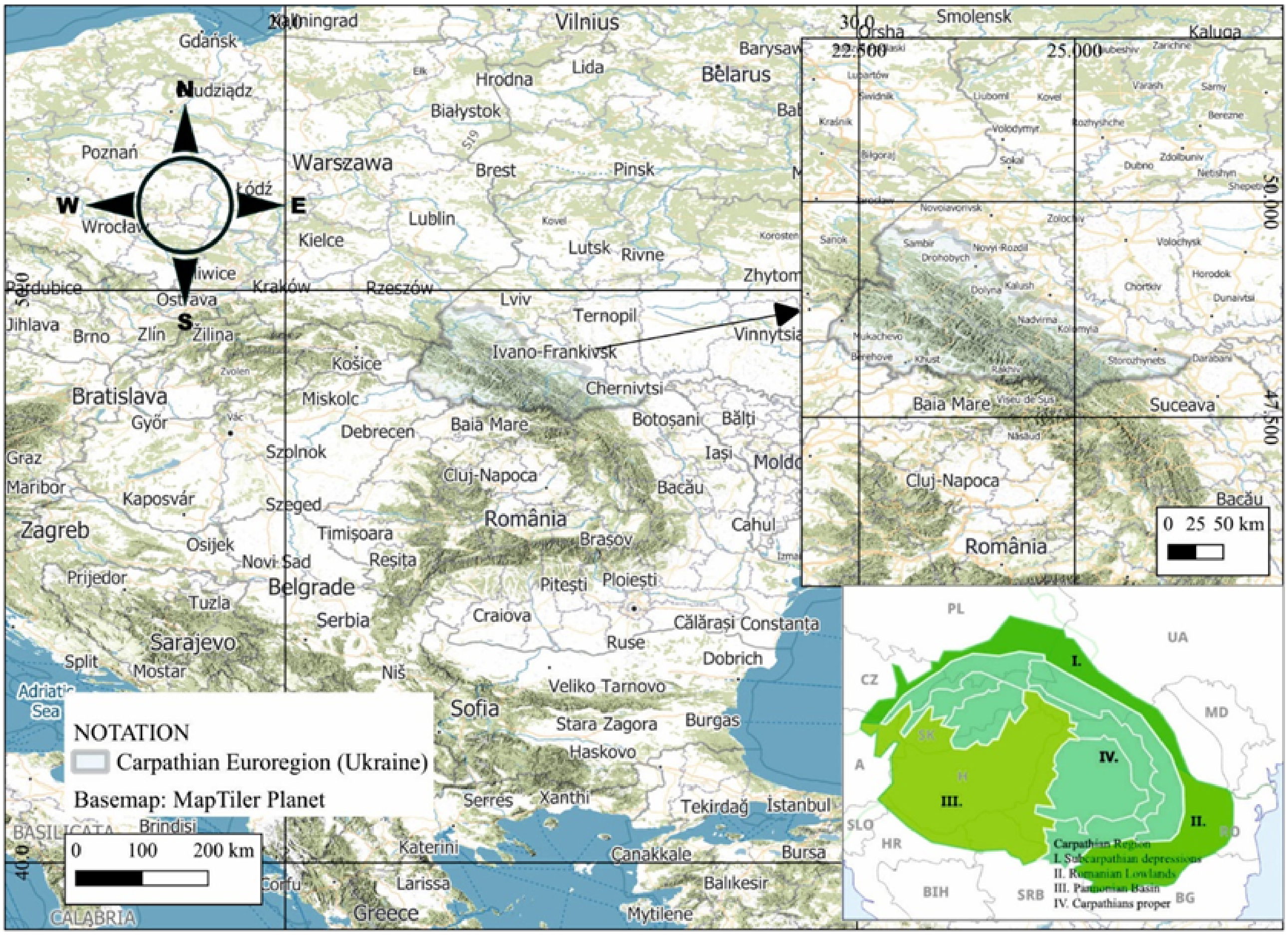

Figure 1. Research area.

2.2. Tourism in the Carpathian National Nature Park

Natural prerequisites for tourism development.

The Carpathian National Nature Park (Carpathian NNP) is one of the most famous nature conservation areas in Ukraine. It is located within the Ivano-Frankivsk region and covers mountain ranges that are home to exceptional biodiversity, picturesque landscapes, and cultural heritage. Geographically, the park includes part of the highest massif of the Ukrainian Carpathians—Chornogora, where the highest peak of Ukraine—Mount Hoverla (2061 m)— rises.

The park has a temperate continental climate with significant altitude gradients. In the lower mountain belt, the average annual temperature is around +7 °C, while in the high mountains it is close to zero. Precipitation reaches 1000–1400 mm per year, which contributes to the formation of a dense hydrographic network. The sources of many rivers are concentrated here, including the Prut, which forms the Huk Waterfall – one of the most popular natural attractions of the park.

The variety of altitude zones determines the high diversity of flora and fauna. Within the park, there are spruce, beech, and mixed forests, alpine and subalpine meadows, which are habitats for rare species of flora and fauna. Brown bears, lynxes, capercaillies, and numerous species of bats have been preserved here. Such natural resources are a prerequisite for the development of educational, recreational, and ecotourism.

Tourist infrastructure and routes.

The Carpathian National Nature Park has one of the most developed systems of tourist routes among Ukrainian parks. Dozens of ecological and hiking trails have been officially established, among which the routes to Hoverla, Petros, and Pip Ivan Chornohirskyi are particularly popular. In the low-mountain areas, there are active routes to waterfalls, rock complexes, and lakes, such as Lake Nesamovite, which is considered a symbol of Chornohora.

The park has infrastructure for organised recreation: tourist shelters, green tourism estates, camping sites, ski slopes, and lifts in the surrounding areas (especially in Vorokhta and on the Yablunytsky Pass). Much of this infrastructure is integrated with the traditional life of local communities, which offer tourists accommodation, food, and cultural programmes.

Tourist flows.

Hundreds of thousands of tourists visit the Carpathian National Nature Park every year. Over the last decade, there has been a steady trend towards growth in tourist flows, which is linked to increased interest in domestic tourism, the development of transport accessibility, and the growing popularity of active leisure activities. During peak seasons (summer months and winter holidays), the number of visitors increases sharply. The most visited site remains Mount Hoverla, which welcomes tens of thousands of tourists every year.

It is important to note that tourist flows in the Carpathian National Nature Park are seasonal in nature. In summer, hiking, ecological excursions, cycling, and camping prevail, while in winter, the number of visitors to ski resorts and recreation centres increases. This concentration puts significant pressure on natural complexes, especially in the high mountains.

Tourism economy.

Tourism in the Carpathian National Nature Park is one of the key factors in local development. For residents of the surrounding villages (Yaremche, Vorokhta, Mykulychyn, Polianytsia), the tourism sector provides jobs, stable income, and small business development. The main areas of activity are the provision of accommodation, catering, rental of tourist equipment, organisation of excursions, as well as crafts and the sale of souvenirs.

Thanks to tourists, investments are coming into the region, new businesses are being created, and infrastructure is being restored. At the same time, economic benefits are accompanied by challenges: uneven distribution of income, seasonality of work, and risks of infrastructure overload.

Types of tourism and recreation.

Various forms of tourism are developing in the Carpathian National Nature Park:

Recreational—outdoor recreation, picnics, camping.

Cognitive and educational— excursions to natural monuments, botanical and geological sites.

Active—hiking, cycling, and horse riding routes, rafting on mountain rivers.

Winter— skiing, snowboarding, winter hiking.

Ecotourism—visiting areas with minimal impact on the environment, participating in nature conservation and educational programmes.

Cultural and ethnographic – getting to know Hutsul traditions, folklore, cuisine, and crafts.

Environmental challenges of tourism.

Intensive tourism development creates a number of environmental problems. First of all, this is the degradation of vegetation due to trampling on popular routes, soil erosion on slopes, and littering of the territory. In the highlands, there is a decrease in the regenerative capacity of alpine meadows. The construction of hotels, roads, and lifts leads to the fragmentation of habitats and the loss of natural landscapes.

Another problem is noise and light pollution, which affects animal behaviour. Tourist transport and the increase in the number of private cars in resort villages cause additional emissions.

Tourism management and sustainable development strategies.

The park's management is actively working to combine tourism development with nature conservation. To this end, the following measures are being implemented:

A system of ecological routes with equipped parking areas and information stands.

Visitor management in the most sensitive areas.

Educational programmes for tourists and the local population aimed at raising environmental awareness.

Development of ecotourism as an alternative to mass tourism.

Cooperation with local communities to create jobs and support traditional lifestyles.

The socio-cultural dimension of tourism.

In addition to its economic significance, tourism in the Carpathian National Nature Park contributes to the preservation and promotion of cultural heritage. Tourists have the opportunity to get acquainted with Hutsul music, folk dances, and traditional holidays. Local communities demonstrate ancient crafts such as weaving, wood carving, and pottery. This interaction shapes the region's unique identity, which is attractive to tourists and stimulates the development of cultural initiatives.

Prospects for development.

The future development of tourism in the Carpathian National Nature Park is linked to the search for a balance between economic interests and environmental constraints. Important tasks include:

establishing recreational load standards for different parts of the park;

developing 'green' transport and environmentally friendly means of transport;

supporting sustainable businesses that use local resources rationally;

applying modern monitoring technologies (GIS, satellite data) to assess the state of ecosystems;

integrating local communities into tourism planning processes.

Thus, the Carpathian National Nature Park is a unique combination of natural beauty, cultural heritage, and tourism potential. Tourism here acts as a driver of economic development, but at the same time requires a clear management system to preserve the unique mountain ecosystems for future generations.

2.3. Data Sources

A combination of satellite, reanalysis, and ground-based data was applied to examine vegetation and climate dynamics.

Remote sensing data.

Sentinel-2 MSI and Landsat (5 TM, 7 ETM+, and 8 OLI) imagery were the primary sources for vegetation monitoring. Their spectral resolution, particularly the red and near-infrared bands, enables reliable calculation of vegetation indices such as the NDVI. Only cloud-free scenes from the vegetation season (May–September) were included to minimise atmospheric distortions. Landsat imagery allowed reconstruction of NDVI trends starting from 2000, while Sentinel-2 data provided higher spatial detail (10–20 m) for the period after 2015.

Climate data.

To assess long-term temperature variability, the ERA5-Land reanalysis [29] was employed. It provides continuous daily data on near-surface air temperature and precipitation with a spatial resolution of ~9 km, covering the period 1980–2024. These data were aggregated to seasonal and annual scales. Additionally, long-term observations from regional meteorological stations were used to validate ERA5-based trends.

Topographic data.

The Shuttle Radar Topography Mission (SRTM) digital elevation model (30 m) was integrated to analyse altitudinal patterns of vegetation change, since mountain ecosystems in the Carpathians are highly sensitive to elevation-dependent climatic variation.

Vegetation index calculation.

Vegetation dynamics were assessed using the Normalized Difference Vegetation Index (NDVI), a widely applied indicator of plant biomass and photosynthetic activity. NDVI was calculated according to the formula (1):

$$NDVI = (NIR - RED) / (NIR + RED) \tag{1}$$

In this formula, NIR is reflectance in the near-infrared band, and RED is reflectance in the red band. For each year, seasonal composites (May–September) were generated in order to reduce the impact of cloud contamination and short-term anomalies. Annual mean NDVI values were then extracted for the study region and for selected zones of intensive recreational use.

Climate trend analysis.

Climatic variability was examined through long-term temperature series derived from ERA5-Land and meteorological observations. Mean annual and seasonal air temperature trends were computed, with a focus on the warm (May–September) period, which coincides with the active vegetation season. Linear regression was applied to detect directional changes (2)[30]:

$$T(t) = a \cdot t + b \tag{2}$$

In the formula (2), T(t) is the mean seasonal or annual temperature, a is the slope (rate of change), and b is the intercept. Precipitation data were also reviewed to contextualise vegetation responses, but were not included in the main modelling stage.

Data processing workflow.

All remote sensing and reanalysis datasets were processed within the Google Earth Engine (GEE) cloud computing environment. This allowed automated retrieval of satellite imagery, application of cloud masking algorithms, generation of seasonal composites, and calculation of NDVI time series for the period 2000–2024. The use of GEE ensured reproducibility, scalability, and integration of large datasets without local computational limitations.

Statistical analysis was carried out in Python and STATISTICA. Correlation analysis was applied to explore relationships between NDVI values and air temperature anomalies. Trend significance was evaluated using Student's t-test at the 0.05 level.

Cartographic visualization.

The spatial distribution of NDVI and its changes over time were mapped using QGIS software. Cartographic products included annual mean NDVI maps, zonal statistics by administrative regions, and overlays with areas of intensive recreational tourism. This approach enabled spatial interpretation of vegetation dynamics in relation to both climatic variability and tourism pressures.

3. Results

3.1. Climate-Vegetation Interactions within the Carpathian National Nature Park

During the study period (**Table 1, Figure 2)**, NDVI values ranged from 0.52 (2016) to 0.75 (2017), which generally corresponds to a high level of vegetation cover development. The average value for the period is about 0.65, which indicates the stable preservation of forest cover and high biological productivity of the ecosystems of the Carpathian National Nature Park. The lowest index value in 2016 may be associated with unfavourable meteorological conditions, in particular low temperatures (average only 5.35 ºC) and low humidity (dew point 2.34 ºC). This probably caused some inhibition of plant photosynthetic activity. In contrast, peak NDVI values in 2017, 2021, and 2024 (0.74–0.75) show a high level of green cover, indicating favourable climatic conditions and vegetation recovery after periods of stress.

An analysis of temperature characteristics indicates a clear trend towards an increase in average annual temperatures. While the average values ranged from 5.3 to 9.3 °C between 2015 and 2017 (taking into account the incomplete data for 2015), by 2024 the temperature had risen to 7.1 °C, which is over 1.5 °C higher than the values for 2016–2017. At the same time, dew point values increased from 2.31–2.34 °C at the beginning of the review period to 3.58 °C in 2024. This suggests an increase in air humidity and, in general, a warming of the region's climate.

Table 1. Indicators of vegetation and climatic conditions in the Carpathian National Nature Park.

Year	NDVI	Dew Point, ºC	Temperature, ºC
2015 (July–December)	0.66	6.24	9.36
2016	0.52	2.34	5.35
2017	0.75	2.31	5.35
2018	0.71	3.06	5.96
2019	0.67	3.27	6.30
2020	0.63	2.82	5.90
2021	0.74	1.68	4.59
2022	0.55	2.18	5.31
2023	0.56	3.34	6.28
2024	0.74	3.58	7.10
2025 (January–June)	0.65	0.05	3.65

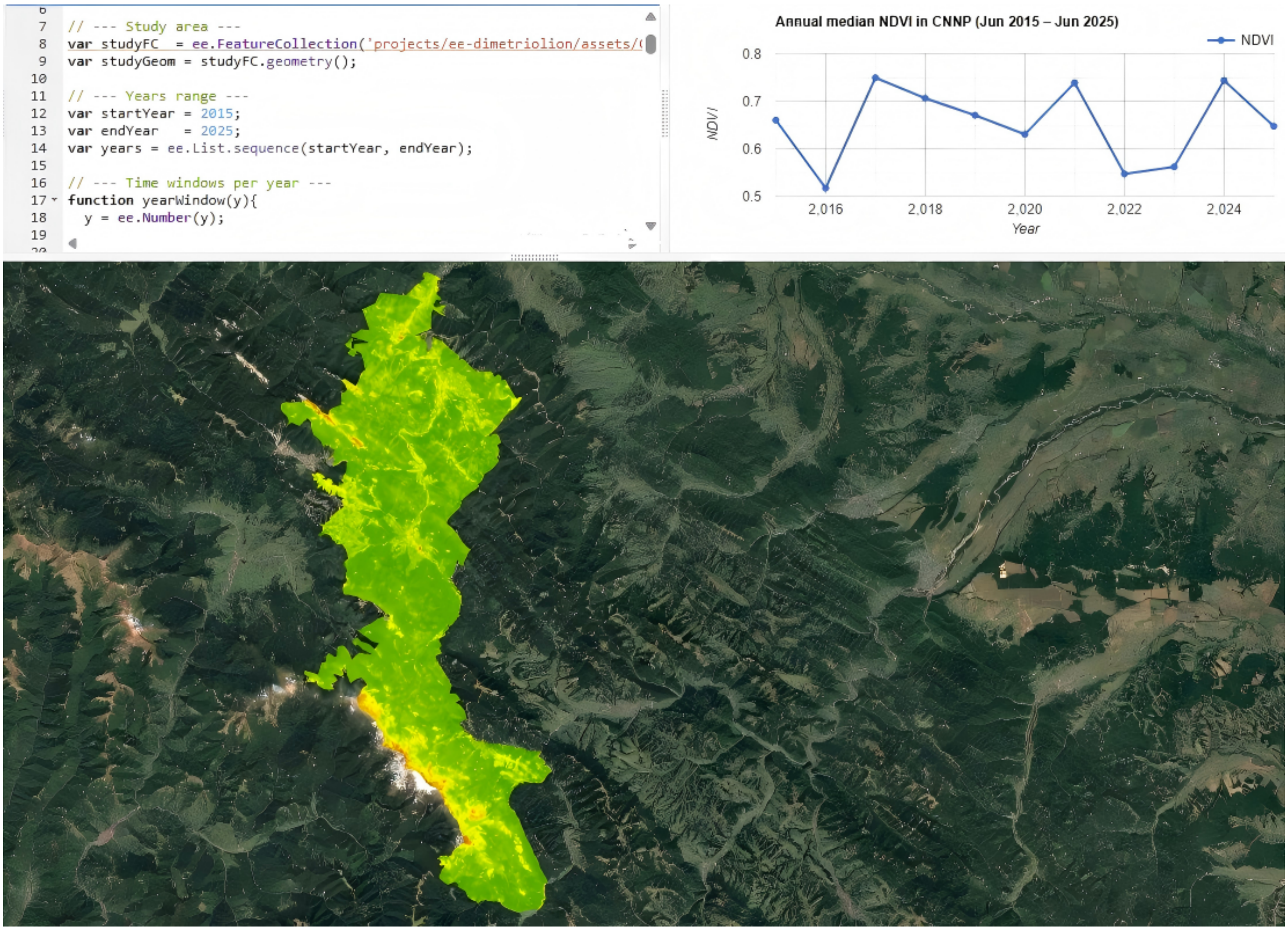

Figure 2. Script window with NDVI map and graph within the Carpathian National Nature Park.

An important point is the consistency of NDVI fluctuations with climatic parameters. In years with relatively low temperatures and dew points (e.g., 2016 and 2022), NDVI values decreased sharply (to 0.52 and 0.55, respectively). This confirms the dependence of vegetation cover on temperature and humidity: low temperatures and lower air humidity reduce photosynthesis rates, resulting in reduced leaf area and a lower vegetation index. Conversely, years with warmer and more humid conditions (such as 2017, 2021, and 2024) are characterised by high NDVI values, reflecting the active growth and development of vegetation.

Interestingly, the period from 2020 to 2023 shows a relative stabilisation in temperature (around 5.9–6.3 °C) and dew point (around 2.8–3.3 °C). However, the Normalised Difference Vegetation Index (NDVI) was not at its maximum during these years and even decreased to 0.55–0.56 in 2022–2023. This may indicate that additional factors, beyond climatic ones, have affected the state of vegetation, such as local landslide processes, anthropogenic pressure (e.g., recreation and logging), and possible diseases or damage to tree stands. Therefore, temperature and humidity alone do not always fully explain NDVI dynamics, and a comprehensive approach that considers anthropogenic and biotic factors is required.

Analysis of the first half of 2025 shows a decrease in average temperatures (3.65 °C) and dew point (0.05 °C), which is normal for the January–June period. At the same time, however, NDVI remains relatively high (0.65), confirming that vegetation is in good condition even in the colder conditions at the beginning of the year. This may suggest that the ecosystems of the Carpathian National Nature Park are resilient to short-term climate fluctuations.

3.2. The Influence of Seasonality on the Formation and Functioning of the Tourist and Recreational Base

Seasonality is one of the key factors determining the dynamics of tourist flows in the Carpathian region and directly influences the development of the hotel and recreation infrastructure. The greatest load falls on the summer-autumn period, when visitor numbers peak thanks to favourable climatic conditions, high natural beauty, and opportunities for active recreation. At the same time, the winter season remains important due to the functioning of the ski infrastructure, which stimulates the expansion of the network of hotels, guesthouses, and recreational complexes. This cyclical nature creates both advantages (growth in economic revenues, employment) and challenges, including ecosystem overload, local disturbances to the natural environment, and the need for rational planning of tourist infrastructure. The modern development of the hotel and recreational base should be based on the principles of sustainability, combining economic benefits with the protection of the Carpathian National Park.

3.3. Assessment of the NDVI Index

Assessment of the spatial distribution of the NDVI index for 2025 in the Carpathian National Nature Park allows us to detail the relationships between the state of vegetation cover, climatic conditions, and the level of anthropogenic pressure. The resulting map shows predominantly high NDVI values (0.6–0.8), indicating stable productivity of forest and meadow ecosystems. However, alongside the generally positive background, there are areas with locally reduced values (0.3–0.5), which can be found in areas of intensive human use and in areas sensitive to natural degradation processes.

Spatial differences.

The highest NDVI values were recorded in the central and northern parts of the park, where continuous areas of spruce and beech forests exist. These areas are characterised by sufficient humidity and a relatively low level of recreational pressure, which provides favourable conditions for active photosynthetic activity. At the same time, in the southern and south-eastern areas, particularly on the slopes of Chornogora and in the vicinity of the massifs, where popular tourist routes to Hoverla and Petros are concentrated, a decrease in NDVI is observed. Here, the index value decreases to 0.45–0.55, which may be due to trampling of the grass cover, the development of erosion processes, and local deforestation.

In the vicinity of Yaremche, Vorokhta, and aling the corridor to the Bukovel tourist cluster, there are noticeable areas with reduced NDVI. These areas overlap with zones of active infrastructure development, such as roads, hotels, ski lifts, where natural vegetation cover has been replaced by anthropogenic objects. This confirms the conclusion about the spatial heterogeneity of vegetation, which is determined not only by climatic factors but also by the intensity of economic activities.

Comparison with previous years.

In the context of the dynamics of 2015–2024, the average NDVI value in 2025 (0.65) corresponds to the long-term average. This indicates a certain stability of ecosystems, despite fluctuations in climatic parameters and local pockets of degradation. However, unlike the peak years (2017, 2021, 2024), when the index exceeded 0.74, the current indicator points to a lack of maximum productivity. This may be due to both the seasonal nature of the data (analysis for January–June 2025) and the cumulative impact of anthropogenic pressure.

It is worth noting that even in the first half of the year, when average temperatures and dew points were significantly lower than in previous years (3.65 °C and 0.05 °C, respectively), the NDVI remained relatively high. This indicates the resilience of the park's forest and grassland ecosystems to short-term climatic stresses. This is likely influenced by the ability of coniferous forests to maintain green cover throughout the year and the gradual restoration of damaged areas.

The 2025 map shows several important patterns (**Figure 2**):

Forest areas as NDVI stabilisers. High values within the central areas of the park confirm that forests maintain the highest level of ecological stability. They are a key factor in supporting climate regulation, preventing erosion, and preserving biodiversity.

Tourist concentration areas as centres of index decline. Areas around Hoverla, Petros, and within the tourist corridor to Bukovel demonstrate a spatial correlation between recreational load and NDVI decline. This confirms the cumulative effect of tourism on the state of vegetation cover.

Climate resilience. Despite the relatively cold start to 2025, the NDVI remained high. This indicates that short-term climate anomalies are not a determining factor in degradation and that anthropogenic factors have a greater impact.

Local risks. Areas of reduced vegetation in the southern part of the park indicate potential hotspots of erosion and degradation that require increased attention to prevent the expansion of disturbed areas.

The results show that the state of vegetation in the Carpathian National Nature Park in 2025 can be assessed as stable overall, with an average NDVI of 0.65. However, spatial analysis has identified areas where negative dynamics are observed, particularly in areas of active tourism and infrastructure development. This confirms the need for comprehensive management of the territory, taking into account the spatial heterogeneity of anthropogenic pressure.

Quantitative perspective. Analysis of vegetation dynamics suggests that areas under high recreational pressure have experienced an approximate 10–30% reduction in green cover compared to the most productive periods. This reduction is spatially heterogeneous, concentrated around major tourist routes and infrastructure clusters. These findings highlight the need for targeted management strategies, including zoning, visitor regulation, and ecological monitoring, to maintain the long-term sustainability of Carpathian ecosystems.

Thus, the combination of climate data and the NDVI index allows us to conclude that the main challenge for the conservation of the park's ecosystems in the coming years will not be so much short-term climate variability as the intensity of recreational use and infrastructure development. The creation of a spatially differentiated monitoring system will be a key tool in supporting the ecological sustainability of the territory.

4. Discussion

The results confirm that vegetation in the Carpathian region is highly sensitive to the combined effects of climatic anomalies and recreational pressure. This study demonstrates the value of combining NDVI time-series analysis with spatial indicators of tourism intensity. This approach enables us to distinguish between areas of critical degradation and zones of higher ecological resilience. This approach goes beyond traditional vegetation monitoring by linking ecosystem responses directly to quantifiable human activities.

This integrative perspective reveals that areas with concentrated infrastructure development and peak seasonal visitor numbers are most vulnerable to habitat fragmentation and reduced regeneration capacity, whereas zones with moderate use show higher adaptive potential. These findings highlight the need for spatially differentiated management strategies, including zoning, ecological carrying capacity thresholds, and the promotion of low-impact tourism infrastructure.

By aligning vegetation monitoring with tourism management, the study provides a framework for adaptive governance that reconciles the socio-economic benefits of tourism with the long-term integrity of the Carpathian ecosystem.

4.1. SWOT Analysis: Sustainable Development and Tourism

Assessing tourism development prospects in the Carpathian region from a sustainability perspective requires a critical evaluation of strengths, weaknesses, opportunities, and threats shaped by natural, socio-economic, and environmental factors. The SWOT methodology enables integration of environmental observations with socio-economic indicators, which is particularly relevant given the increasing anthropogenic pressure on Carpathian ecosystems.

Strengths include extraordinary natural diversity, encompassing high-altitude meadows, subalpine and alpine complexes, mountain forests, and unique hydrological features. This mosaic of landscapes attracts recreation and ecotourism, while biodiversity, confirmed by consistently high NDVI values, provides a foundation for long-term sustainable tourism strategies. Other assets are established recreational traditions, experience in international cooperation within the Carpathian Convention, and growing public awareness of nature conservation, which fosters demand for environmentally friendly tourism.

Weaknesses relate to the challenge of balancing infrastructure development with environmental constraints. Seasonal tourist flows generate uneven ecosystem loads: summer and autumn coincide with peak vegetation productivity, and winter involves landscape modifications for ski resorts. The absence of uniform standards for acceptable recreational load increases the risk of local degradation of flora and soil cover, as evidenced by NDVI declines in 2016 and 2022–2023. Limited integration of environmental monitoring into tourism management further complicates adaptive decision-making.

Opportunities arise from growing interest in environmental practices and 'green' technologies, enabling new visitor management models that reconcile economic development with biodiversity conservation. The application of remote sensing and GIS facilitates vegetation monitoring and supports adaptive tourism planning. Development of ecotourism, educational programs, and community involvement can establish economically viable and environmentally sound practices. European integration and Ukraine's participation in international initiatives provide additional avenues for funding and adoption of best practices.

Threats include climate change, manifested by rising temperatures and shorter snow cover, which challenge winter tourism and promote infrastructure expansion into sensitive areas. Unregulated growth of hotel and transport networks increases pressure on natural resources, and the global tourist influx may exceed ecological carrying capacities. Economic instability may prioritize short-term gains over long-term environmental sustainability.

In conclusion, the SWOT analysis highlights the duality of current trends: abundant natural resources and international cooperation support sustainable tourism, whereas intense recreational flows, climate change, and regulatory weaknesses create risks that may offset these advantages. This underscores the need for integrated management combining environmental monitoring, remote sensing, and socio-economic approaches, treating sustainable development as a practical tool to balance economic benefits with preservation of the Carpathians' natural potential.

4.2. Eco-Tourism and Its Impact on Landscapes and Biodiversity

In the context of the current development of the Carpathian region, particularly in its Ukrainian part, eco-tourism is emerging not only as an innovative form of tourism but also as a powerful factor capable of shaping the dynamics of landscapes and the state of biodiversity. Your research has shown that NDVI fluctuations, particularly the decline in 2016 and 2022–2023, may be the result not only of climatic fluctuations but also of the cumulative impact of anthropogenic pressure, including tourism infrastructure. This raises the question of the extent to which the development of eco-tourism practices affects vegetation structure, soil characteristics, and overall ecosystem integrity.

On the one hand, eco-tourism opens up opportunities to strengthen the protective functions of nature conservation areas by attracting resources for monitoring and educational activities. Existing data show that national parks and biosphere reserves, such as Uhol-Shyrokyi Luh and the Carpathian Biosphere Reserve, are introducing eco-trails that allow tourists to access pristine forest complexes without significantly interfering with the natural structure. At the same time, eco-trails, when properly planned and marked, significantly reduce the risk of damage to rare vegetation or erosion compared to the chaotic movement of visitors through the landscape. Such routes, which run through Uholka-Shyrokyi Lug, create a trusting contact between people and nature, ensuring minimal impact on the ecosystem.

On the other hand, international experience demonstrates the duality of ecotourism: timely management can be a driver of biodiversity conservation, while the absence of regulatory mechanisms can pose a risk to sensitive ecosystems. For example, in the Dadia-Lefkimi-Soufli National Park (Greece), WWF eco-initiatives, combined with environmental education, have helped to preserve populations of endangered birds of prey and created new jobs, demonstrating that eco-tourism can bring synergistic environmental and socio-economic benefits. Such strategic approaches open the way to international experience for Ukrainian nature conservation structures.

It is important to understand that eco-tourism in the Carpathians is implemented in conditions of complex mountain geography, which makes ecosystems extremely sensitive to even moderate loads. Comparative studies confirm that even moderate levels of visitation can alter soil structure, cause vegetation cover to flatten, or disrupt local hydrological processes. However, your study also found that during periods of reduced temperature and humidity (2016, 2022–2023), the NDVI index declines more than would be predicted by climate factors alone, indicating the role of additional anthropogenic causes – including tourist activity.

The use of eco-tourism as a platform for education and mobilisation of local communities is also relevant. Relevant initiatives mentioned in Carpathian development projects include the integration of international practices, student training, and practical involvement in national parks – this can shape a new generation of professionals capable of managing recreational activities in sensitive landscapes in accordance with the principles of sustainability. Combining your remote sensing methodology with eco-tourism practices paves the way for adaptive management: combining GIS monitoring, NDVI analysis, and tourist flows allows for the timely identification of tourist hotspots and the implementation of corrective measures – access restrictions, trail marking, recreation area development, flow redirection, etc.

Ultimately, the effectiveness of eco-tourism depends on whether it can combine landscape and biodiversity protection with economic aspects. Your work emphasises that even during periods of bad weather (low temperatures in the first half of 2025), the NDVI remained consistently high, indicating ecological stability. This is an important prerequisite: eco-tourism cannot only be a tool for conservation, but also contribute to strengthening the resilience of ecosystems through attention to their monitoring and protection. Thus, eco-tourism in the context of the Carpathians is a complex phenomenon with multi-layered consequences: it can preserve rare landscapes and diversify the economy of communities if it is integrated into an environmental management system, equipped with remote monitoring tools, has regulatory mechanisms, and includes active public education. Otherwise, its potential may become a source of implicit degradation processes, especially in the context of seasonality and climate challenges.

5. Conclusions

This study confirmed that vegetation in the Carpathian region demonstrates high stability, with NDVI values reflecting generally strong ecosystem productivity during the past decade. At the same time, specific years (2016, 2022–2023) revealed temporary declines, underlining the vulnerability of forest ecosystems to external stressors.

The analysis also highlighted the strong role of tourism seasonality. Periods of intensive recreational use coincide with peak vegetation activity, which increases ecological risks. Winter recreation, though less synchronized with vegetation growth, produces long-term structural impacts through infrastructure development.

Quantitative assessment of vegetation change. A comparison of NDVI values between the peak years of 2017, 2021, and 2024, and the year 2025, indicates an average decline from 0.74 to 0.65, corresponding to a reduction of approximately 12–13% in the cover of photosynthetically active vegetation in the most affected areas. Localised hotspots, particularly near Hoverla, Petros, and the Bukovel corridor, show a decrease from 0.7–0.75 to 0.45–0.55, implying a 25–35% reduction in green cover due to the combined effects of trampling, erosion, and infrastructure expansion. These quantitative estimates highlight the spatial heterogeneity of vegetation loss and emphasise the need for targeted management measures in areas subject to high levels of recreation.

The findings stress the importance of sustainable tourism planning. Management strategies should prioritize maintaining vegetation resilience, minimizing localized degradation, and integrating ecological indicators (such as NDVI) into monitoring systems. Future research should focus on coupling remote sensing data with detailed assessments of tourist flows to develop adaptive models for balancing conservation and recreational use.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] Feketa, I., 2014. The characteristic of vegetation of a mountain valley Runa of Carpathians in conditions of anthropogenous transformation. Visnyk of the Lviv University. Series Geography. 45, 137–143. DOI: https://doi.org/10.30970/vgg.2014.45.1158

[2] Vynar, N.V., 2015. Taking into account the criteria of sustainable development in the management of tourist and recreational areas of the Carpathian region. Sci-

entific Bulletin of Uzhhorod University: Series Economics. 2, 132–136. Available from: http://nbuv.gov.ua/UJRN/Nvuuec_2015_2_24 (in Ukrainian)
[3] Brovina, F., Sallaku, D., 2024. Sustainable development of forest parks for active recreation: A balance between nature conservation and physical education. Ukrainian Journal of Forest and Wood Science. 15(3), 165–179. DOI: https://doi.org/10.31548/forest/3.2024.165
[4] Kholiavchuk, D., Shkaieva, D., 2024. The LIA climate and environmental changes in the Carpathians: review. Geoconcept Journal. 1, 45–79. Available from: https://geoconcept-journal.com/index.php/geo/article/view/301/228 (in Ukrainian)
[5] Ivanyshyn, V., Kasiyanchuk, D., 2024. Analysis of the Impact of Climate Change on the Vegetation of the Perehinsk Territorial Community in Ukraine. Grassroots Journal of Natural Resources. 7(2), 199–215. DOI: https://doi.org/10.33002/nr2581.6853.070210
[6] Maliarchuk, O.M., Palahniuk, M.M., Bzunko, H.B., 2025. Socio-economic processes in Prykarpattia: From forced industrialization to the development of tourist and rehabilitation infrastructure, 1st ed. Baltija Publishing: Riga, Latvia. pp. 1–256.
[7] Ministry of Ecology of Ukraine, 2003. Vertical vegetation zoning in the Ukrainian Carpathians. Government Report, 12 May 2003. Ministry of Ecology of Ukraine: Kyiv, Ukraine. (in Ukrainian)
[8] Mykhailyk, O., 2022. River ecosystems of the Ukrainian Carpathians: natural features, and urban planning organization of coastal territories. Urban Development and Spatial Planning. 81, 263–273. DOI: https://doi.org/10.32347/2076-815x.2022.81.263-273
[9] Turchyn, O., 2021. Ecotourism in the Carpathians: main locations for travel. Available from: https://nadfermoiu.com/ekoturyzm-v-karpatakh-holovni-lokatsii/ (in Ukrainian)
[10] Watson, J.E.M., Dudley, N., Segan, D.B., et al., 2014. The performance and potential of protected areas. Nature. 515(7525), 67–73. DOI: https://doi.org/10.1038/nature13947
[11] Monz, C.A., Pickering, C.M., Hadwen, W.L., 2013. Recent advances in recreation ecology and the implications of different relationships between recreation use and ecological impacts. Frontiers in Ecology and the Environment. 11(8), 441–448. DOI: https://doi.org/10.1890/120358
[12] Buckley, R., 2012. Sustainable tourism: Research and reality. Annals of Tourism Research. 39(2), 528–546. DOI: https://doi.org/10.1016/j.annals.2012.02.003
[13] Gössling, S., Hall, C.M., Scott, D., 2015. Tourism and Water, 1st ed. Channel View Publications: Bristol, UK.
[14] European Environment Agency, 2016. Climate Change, Impacts and Vulnerability in Europe 2016. European Environment Agency: Copenhagen, Denmark.
[15] Carpathian Convention, 2014. Framework Convention on the Protection and Sustainable Development of the Carpathians. Carpathian Convention: Vienna, Austria.
[16] Kholiavchuk, D., Gurgiser, W., Mayr, S., 2024. Carpathian Forests: Past and Recent Developments. Forests. 15(1), 65. DOI: https://doi.org/10.3390/f15010065
[17] Kondur, O., Kopchak, Y., Kopchak, L., 2014. Role of the Tourism Sector in Sustainable Development of the Carpathian Region: Social, Educational and Economic Aspects. Journal of Vasyl Stefanyk Precarpathian National University, 1(2–3), 119–122. DOI: https://doi.org/10.15330/jpnu.1.2-3.119-122
[18] Matviichuk, L.Y., Barskyi, Y.M., Lepkyi, M.I. (Eds.), 2023. Tourism Development Prospects in Ukraine and the World: Management, Technologies, Models, 9th ed. VIP Lutsk National Technical University Publishing House: Lutsk, Ukraine. 388 p. Available from: https://philpapers.org/archive/ZHZSSD.pdf (in Ukrainian)
[19] Sentinel-2, 2015. European Space Agency (ESA). Sentinel-2 User Handbook. European Space Agency: Paris, France. Available from: https://sentinels.copernicus.eu/documents/247904/685211/Sentinel-2_User_Handbook
[20] QGIS Development Team, 2023. QGIS Geographic Information System. Open Source Geospatial Foundation Project. QGIS 3.38. DOI: https://doi.org/10.5281/zenodo.7585734
[21] Google Earth Engine (GEE), 2018. A planetary-scale platform for Earth science data & analysis. Available from: https://earthengine.google.com/
[22] Muñoz Sabater, J., 2019. ERA5–Land monthly averaged data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: https://doi.org/10.24381/cds.68d2bb30
[23] IPCC, 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK. DOI: https://doi.org/10.1017/9781009325844
[24] Lu, Y., Yu, Y., Sun, L., et al., 2025. NDVI based vegetation dynamics and responses to climate change and human activities at Xinjiang from 2001 to 2020. Scientific Reports. 15, 25848. DOI: https://doi.org/10.1038/s41598-025-11677-5
[25] Dube, K., Nhamo, G., 2025. Weather and climate challenges facing urban Mountain National Park destinations. Cogent Social Sciences. 11(1). DOI: https://doi.org/10.1080/23311886.2025.2548861
[26] Matyukira, C., Mhangara, P., 2024. Advances in vegetation mapping through remote sensing and machine learning techniques: a scientometric review. European Journal of Remote Sensing. 57(1). DOI: https:

//doi.org/10.1080/22797254.2024.2422330

[27] Yang, Q., Jiang, C., Ding, T., 2023. Impacts of extreme-high-temperature events on vegetation in North China. Remote Sensing. 15(18), 4542. DOI: https://doi.org/10.3390/rs15184542

[28] Mitra, A., Paul, S., 2025. Balancing Mountain Tourism, Cultural Heritage, and Environmental Stability: Strategies and Challenges in Sustainable Development. In Balancing Mountain Tourism, Cultural Heritage, and Environmental Stability. IGI Global: Hershey, PA, USA. pp. 31–54.

[29] Schaaf, C., Wang, Z., 2021. MODIS/Terra+Aqua BRDF/Albedo Daily L3 Global – 500m V061. DOI: https://doi.org/10.5067/MODIS/MCD43A3.061

[30] Kasiyanchuk, D., 2022. Study of temporary climate change within the boundaries of the Carpathian region and their relationship with global temperature fluctuations. Ecological Sciences. 42(3), 131–135. DOI: https://doi.org/10.32846/2306-9716/2022.eco.3-42.21 (in Ukrainian)