UDC 528.88:502.75(477.87)
DOI https://doi.org/10.32846/2306-9716/2025.eco.6-63.42

REMOTE SENSING-BASED EVALUATION OF VEGETATION DYNAMICS IN MOUNTAIN PROTECTED AREAS OF THE CARPATHIAN REGION

Semak U., Mylenka M., Tsepetsaver H.
Vasyl Stefanyk Carpathian National University
Shevchenka Str., 57, 76018, Ivano-Frankivsk
uliana.semak@cnu.edu.ua

This study offers an in-depth evaluation of satellite technologies for systematic ecosystem monitoring in mountain protected areas, illustrated through a case study of the Carpathian National Nature Park. The research aims to determine the effectiveness of integrating Earth observation data into conservation practice and to justify the advantages of multispectral satellite observations over traditional field-based methods in topographically complex high-altitude landscapes. The capabilities of current monitoring platforms, including the Sentinel satellites of the Copernicus programme and the Landsat system, are analysed with regard to their suitability for regular environmental assessment in mountain ecosystems. Key practical domains of satellite data application are identified, including vegetation and biotope assessment, detection of ecosystem degradation processes, evaluation of conservation management effectiveness, and modeling climate change impacts on mountain landscapes. A seven-year multitemporal analysis of vegetation condition indicators based on Sentinel-2 imagery demonstrates positive ecological dynamics consistent with strengthened protection regimes and natural forest recovery processes. A methodological scheme integrating satellite monitoring with ground-based ecological data collection is proposed to support the development of comprehensive protected area condition databases. The results emphasise the significance of satellite monitoring for improving environmental assessment, enhancing evidence-based conservation governance, and supporting long-term planning for the preservation of mountain protected areas in the Carpathian region. *Key words:* remote sensing, satellite monitoring, protected areas, Carpathian National Nature Park, vegetation indices, ecosystem monitoring, mountain landscapes, biodiversity conservation.

Оцінка динаміки рослинності природоохоронних територій Карпатського регіону за даними дистанційного зондування. Семак У. Й., Миленька М. М., Цепецавер Г. В.
У статті подано оцінку можливостей супутникових технологій для системного екосистемного моніторингу на територіях високогірних природоохоронних об’єктів, представлену на прикладі Карпатського національного природного парку. Метою роботи є визначення ефективності впровадження даних дистанційного зондування Землі у природоохоронну практику, а також обґрунтування переваг багатоспектральних супутникових спостережень над традиційними польовими методами в умовах складного рельєфу високогірних ландшафтів. Аналізовано можливості сучасних платформ моніторингу довкілля, зокрема супутників Sentinel програми Copernicus та системи Landsat, з точки зору їхньої придатності для регулярної екологічної оцінки стану гірських екосистем. Визначено основні практичні напрями використання супутникових даних, зокрема оцінювання стану рослинності та біотопів, виявлення процесів деградації екосистем, оцінювання ефективності природоохоронного менеджменту й моделювання впливу змін клімату на гірські ландшафти. Семирічний аналіз індикаторів стану рослинності на основі супутникових знімків Sentinel-2 засвідчує позитивну екологічну динаміку, що узгоджується з дотриманням режимів охорони та процесами природного відновлення лісових екосистем. Запропонована методологічна схема інтеграції супутникового моніторингу з польовим збором екологічної інформації спрямована на формування комплексних баз даних про стан природоохоронних територій. Результати дослідження підкреслюють важливість супутникового моніторингу для підвищення якості екологічної оцінки, посилення обґрунтованості управлінських рішень у сфері природоохоронної діяльності та підтримки довгострокового планування збереження гірських охоронюваних територій Карпатського регіону. *Ключові слова:* дистанційне зондування, супутниковий моніторинг, природоохоронні території, Карпатський національний природний парк, індекси рослинності, моніторинг екосистем, гірські ландшафти, збереження біорізноманіття.

Relevance of the research. The effective functioning of protected area networks depends on monitoring systems capable of detecting ecological change with sufficient temporal sensitivity and spatial coverage. Traditional field-based survey methods, despite their high resolution at plot level, are constrained by labour demands, logistical challenges, and limited representativeness across heterogeneous terrain [1]. These limitations are particularly relevant to mountainous landscapes, where steep elevation gradients and fragmented access impede regular on-site assessment [2].

The Ukrainian Carpathians encompass forest ecosystems of high European conservation significance, requiring continuous evaluation of vegetation dynamics, disturbance drivers, and conservation outcomes [3]. However, underfunding, institutional capacity gaps, and the extensive size of protected territories complicate comprehensive field monitoring of ecosystem components. In this context, satellite-based Earth observation offers a scalable means of obtaining objective environmental information across broad spatial extents at comparatively low cost [2, 4, 5].

Recent advances in remote sensing have demonstrated strong potential for monitoring vegetation condition, land cover transitions, and disturbance patterns in protected mountain regions [6, 7]. Freely available satellite missions such as Copernicus Sentinel and NASA/USGS Landsat enable regular acquisition of multispectral datasets suitable for calculating vegetation indices, mapping habitat structure, and detecting degradation trajectories [8, 9]. Nevertheless, methodological adaptation remains necessary to align remote sensing outputs with conservation management goals, particularly within regions where institutional integration of geospatial technologies is still emerging [10].

The relevance of strengthening satellite-supported monitoring is further reinforced by climate-induced mountain ecosystem transformations, including upward shifts in vegetation belts and increasing frequency of extreme meteorological events [11]. Additionally, Ukraine's commitments under the Convention on Biological Diversity and the Carpathian Convention require reliable monitoring frameworks and transparent ecological reporting (UNEP, 2007) [12]. Open access to high-resolution satellite datasets presents unique opportunities for conservation authorities with constrained budgets; however, effective uptake depends on methodological frameworks suited to Carpathian ecological and administrative realities.

Analysis of research and publications. The application of remote sensing in ecological monitoring has gained substantial momentum within the international scientific community over the past two decades. Foundational contributions by Drusch et al. (2012) provided the technological basis for deploying the Sentinel-2 mission, which offers multispectral imagery with spatial and temporal characteristics suitable for tracking terrestrial surface processes [8]. Subsequent work highlighted the transformative effect of open-access satellite archives on conservation practice, with Turner et al. (2015) demonstrating that freely available satellite datasets significantly improve biodiversity monitoring capacity, particularly in countries with limited financial resources [13].

The integration of remote sensing in protected area assessment has been structured by the comprehensive review of Nagendra et al. (2013), who synthesized methodological approaches for habitat mapping, biodiversity state evaluation, and threat detection using satellite observations [6]. Parallel to this, researchers advanced the Essential Biodiversity Variables framework, identifying ecological indicators that can be reliably quantified through space-borne data, thus linking conservation monitoring needs with remote sensing potential [4, 10].

Large-scale analyses further confirmed the value of satellite monitoring for evaluating conservation effectiveness. Using Landsat-derived datasets, Geldmann et al. (2019) demonstrated that protected areas play a measurable role in reducing anthropogenic degradation relative to adjacent unprotected territories [7]. In a related field-defining contribution, Hansen et al. (2013) produced the first globally consistent high-resolution map series of forest cover change, establishing an empirical standard that underpins numerous regional forest dynamics assessments [14].

Within the Carpathian region, satellite-based research has yielded important insights into forest change processes. Kuemmerle et al. (2009) documented extensive illegal logging and discrepancies in official reporting across the Carpathians between 1984 and 2010, highlighting the necessity of independent remote sensing-based monitoring. Complementing these findings, Lyalko et al. (2019) investigated remote sensing applications for detecting environmental changes in terrestrial ecosystems of Ukraine that have intensified under recent climatic shifts [15].

Climate-related analyses underpin the interpretation of vegetation trends in mountainous terrain. Spinoni et al. (2015) and Pepin et al., (2025) identified statistically significant warming tendencies and precipitation regime alterations across the European region in latests decades [11, 17], while Körner et al. (2017) established an ecologically grounded classification system for mountain bioclimatic belts, providing a framework for stratifying satellite-derived ecological data in high-relief landscapes [2].

Recent developments indicate a methodological evolution toward integrating satellite analytics, machine learning, and participatory monitoring. Research by Gorelick et al. (2017) introduced the Google Earth Engine platform, which dramatically expanded accessibility to large-scale geospatial computation for conservation applications [17].

Identification of previously unresolved problem components and scientific novelty. Despite increasing use of remote sensing in conservation monitoring, key gaps remain for mountain protected areas. Most research focuses on technical satellite data processing, while practical adoption in park management is rarely assessed – especially considering limited staffing and financial resources typical for Ukrainian conservation agencies [2, 12, 14]. Long-term satellite archives are seldom used to evaluate protected area effectiveness at the individual park level [6, 4], and it remains methodologically challenging to separate natural succession from humaninduced vegetation change due to interacting drivers such as climate and management [11].

The scientific novelty of this work lies in presenting the first continuous, high-resolution seven-year assessment (2017–2024) of vegetation condition for the Carpathian National Nature Park using freely available Sentinel-2 data imagery processed through the Google Earth Engine platform. This approach delivers the initial quantitative evaluation of ecological trends following the park protection regime and provides a foundation for standardized, repeatable monitoring that can facilitate reliable comparisons between protected areas [7]. This framework allows detection of subtle ecological trends essential for evidence-based conservation, with broader applications in forestry, land-use planning, and ecosystem services assessment [4, 12].

Study object characterization. The study was conducted within the Carpathian National Nature Park, located in the northeastern part of the Ukrainian Carpathians in Ivano-Frankivsk Oblast and covering about 515 km². The park extends from foothill zones at approximately 500 meters above sea level to the peak of Mount Hoverla at 2061 meters, producing a clearly defined sequence of vegetation belts. These range from mixed deciduous–coniferous communities in the lower elevations through beech and spruce forests in the mid-mountain zone to subalpine shrubs and alpine meadow formations in the highest areas. Forest ecosystems dominate the landscape, accounting for nearly seventy percent of the territory, with beech stands forming the principal component. The presence of old-growth beech forests recognized within the UNESCO World Heritage network highlights the conservation significance of the area. The fauna of the park includes more than fifty mammal species, including large carnivores and semi-aquatic species characteristic of mountain river valleys, such as brown bear, wolf, lynx, otter, and the critically endangered European mink. Management is based on a zonation system that differentiates strict protection areas, regulated recreation sectors, and territories where traditional land-use practices continue under controlled conditions. This framework supports biodiversity conservation while allowing environmentally compatible tourism and local livelihood activities. Annual visitation exceeds thirty thousand people, with a significant proportion associated with routes leading to Hoverla, the highest summit in Ukraine and a central attraction for mountaineering and nature-based recreation.

Research methodology. This study utilized multi-temporal analysis of Sentinel-2 multispectral imagery (Level-2A, surface reflectance) covering the period from 2017 to 2024. To minimize seasonal effects and maximize comparability, only images from the peak growing season (June–August) were selected. Vegetation indices were computed using 10-meter resolution reflectance data from the red and near-infrared channels.

All data preprocessing and analytical operations were performed within the Google Earth Engine (GEE) cloud platform, which provides direct access to the Sentinel-2 archive and facilitates large-scale remote sensing analysis without local data storage. Automated scripts were developed to streamline image selection, cloud masking, compositing, vegetation index calculation, and export of derived results.

The workflow followed a systematic sequence: Initially, images with less than ten percent cloud cover were identified. Where fully clear observations were unavailable, median composites were assembled to ensure continuous spatial coverage. Topographic corrections were conducted using data from the Shuttle Radar Topography Mission (SRTM), reducing reflectance artifacts caused by slope and variable illumination.

For vegetation assessment, the normalized difference vegetation index (NDVI) was calculated, capitalizing on the distinct spectral contrast between strong absorption in the red and high reflectance in the near-infrared wavelengths exhibited by healthy vegetation. NDVI values were interpreted according to established ecological benchmarks, spanning negative values for open water and soil to high positives for dense, productive vegetation canopies.

Spatial and temporal dynamics of vegetation condition were quantified through pixel-wise NDVI differencing between 2017 and 2024. Summary statistics included mean and standard deviation of NDVI values, distributions of NDVI change, and stratified analyses by elevation belt, allowing for robust examination of spatial heterogeneity and ecological trends across the study area.

Research results and discussion. A multi-temporal analysis of Sentinel-2 imagery from 2017 to 2024 reveals a generally positive trend in vegetation condition across the Carpathian National Nature Park. The average NDVI change of approximately +0.0065 per year indicates a statistically meaningful, gradual improvement in vegetation health over the study period, which is ecologically significant given the park's already well-preserved forest ecosystems and the large monitored area of about 500 km².

Initial NDVI values in 2017 ranged mostly between 0.64 and 0.74, reflecting healthy, continuous forest stands typical of mature mountain forests. The subsequent increase in NDVI values likely signals incremental biomass accumulation and enhanced canopy density rather than a recovery phase from degradation, consistent with slow, progressive development of structural complexity in protected temperate forests.

Spatial analysis demonstrated a generally stable and positive trend in vegetation condition across protected polygons of the Carpathian National Nature Park. Most areas exhibited either stable or incrementally increasing mean NDVI values between 2017 and 2024, reflecting persistent canopy continuity and gradual biomass accumulation characteristic of intact, well-protected mountain forests.

Greater variability in NDVI change was observed in some polygons, which may be explained by differences in land-use history, accessibility, or localized management regimes. No extensive zones of marked NDVI decline were detected, suggesting that the expansion of the protected regime since 2017 has been effective in preventing significant vegetation loss. Polygons that historically experienced selective logging or grazing tended to show slightly higher positive NDVI change, consistent with ongoing natural regeneration processes. This indicates an overall pattern combining stability in long-established forest areas with recovery dynamics where past disturbance occurred.

These results, based entirely on satellite-derived NDVI time series aggregated over protected area boundaries, provide evidence that robust legal protection and administrative controls are contributing to ecological resilience and incremental improvement across the park landscape. Taken together, the results denote a steady improvement trajectory characteristic of mature, well-protected mountain forest ecosystems. Rather than abrupt vegetation rebounds typical of recently abandoned or degraded landscapes, the park exhibits stability at a high ecological baseline followed by incremental gains – consistent with long-term conservation success.

The positive trend in vegetation condition across the Carpathian National Nature Park corresponds with findings that well-protected mountain forests tend to accumulate biomass and increase canopy density gradually over time [2, 6]. The modest but statistically significant rise in NDVI values, observed despite already high initial levels, aligns with patterns described for mature temperate forests where structural diversification progresses incrementally rather than through rapid post-disturbance recovery [4]. This contrasts with trajectories documented in degraded or recently abandoned landscapes, where vegetation indices increase steeply due to pioneer species expansion [14].

The spatial consistency of improvement suggests systemic drivers rather than localized management effects. Studies of protected area performance demonstrate that zoning, restrictions on resource extraction, and regulated recreational pressure contribute to broad-scale ecological stability [7, 11]. The distribution pattern detected in the park corresponds with research showing that effective enforcement reduces illegal logging and grazing impacts in Carpathian forests [18].

The slightly higher improvement magnitude in areas previously affected by selective logging reflects natural regeneration dynamics, consistent with forest recovery models where younger stands exhibit higher productivity and canopy expansion. This indicates the coexistence of old-growth stability and successional renewal, a pattern characteristic of resilient mountain forest landscapes.

Elevation-based differences in NDVI dynamics reflects ecological stratification processes documented for the Carpathians. The stability of the mid-mountain beech–spruce belt reflects optimal climatic and edaphic conditions for dominant forest species, while moderate NDVI increases in subalpine and alpine belts correspond with reported upward vegetation boundary shifts associated with regional warming trends [2, 11, 14]. The absence of widespread degradation aligns with field-based observations and corresponds with evidence that protected status provides a buffering effect against anthropogenic pressures common in unprotected Carpathian forests. This suggests that management measures currently outweigh potential negative climatic or socio-economic stressors.

Overall, the detected trends support the interpretation that long-term protection contributes to maintaining high ecosystem quality while enabling slow, cumulative improvement – an outcome consistent with conservation theory for mature mountain forests [4, 6]. The capacity of multi-temporal satellite monitoring to differentiate gradual ecological trajectories from short-term variability highlights its value for adaptive management, policy planning, and evidence-based evaluation of protected area effectiveness.

Conclusions. The study demonstrates that multi-temporal Sentinel-2 satellite data provide a reliable and cost-effective means of monitoring vegetation dynamics in large mountain protected areas. The seven-year assessment of the Carpathian National Nature Park revealed a consistent positive trend in vegetation condition across most of the territory, offering quantitative evidence of effective protection measures and natural ecosystem resilience. The methodology developed in this research, based on free satellite data, cloud-based processing, and minimal technical requirements, is well suited to the operational constraints of Ukrainian conservation institutions and enables scalable application across parks of different sizes and management regimes. The results underline the importance of integrating satellite observations with field surveys and climatic information to ensure accurate interpretation of ecological changes and establish baseline indicators for long-term monitoring. The approach provides practical value for conservation planning, zoning refinement, and early detection of emerging pressures, and can form the basis for a unified monitoring framework for protected areas throughout the Ukrainian Carpathians. Continued observation, expansion to additional data sources, and integration into national reporting and training systems represent promising directions for future development.

References

1. Lõhmus A., Lõhmus P., Runnel K. A simple survey protocol for assessing terrestrial biodiversity. *PLoS One*. 2018. Vol. 13, No. 12. e0208535. DOI: https://doi.org/10.1371/journal.pone.0208535
2. Körner C., Jetz W., Paulsen J., Payne D., Rudmann-Maurer K., Spehn E. M. A global inventory of mountains for bio-geographical applications. *Alpine Botany*. 2017. Vol. 127. P. 1–15. DOI: https://doi.org/10.1007/s00035-016-0182-6
3. Poliakova L., Abruscato S. Supporting the recovery and sustainable management of Ukrainian forests and Ukraine's forest sector. Bonn: FOREST EUROPE, 2023. 67 p.
4. Pereira H. M., Ferrier S., Walters M., Geller G. N., Jongman R. H. G., Scholes R. J., Wegmann M. Essential biodiversity variables. *Science*. 2013. Vol. 339, No. 6117. P. 277–278. DOI: https://doi.org/10.1126/science.1229931
5. Mao L., Li M., Shen W. Remote sensing applications for monitoring terrestrial protected areas: Progress in the last decade. *Sustainability*. 2020. Vol. 12, No. 12. 5016. DOI: https://doi.org/10.3390/su12125016
6. Nagendra H., Lucas R., Honrado J. P., Jongman R. H. G., Tarantino C., Adamo M., Mairota P. Remote sensing for conservation monitoring. *Ecological Indicators*. 2013. Vol. 33. P. 45–59. DOI: https://doi.org/10.1016/j.ecolind.2012.09.014
7. Geldmann J., Manica A., Burgess N. D., Coad L., Balmford A. A global analysis of protected area effectiveness in reducing human pressure on nature. Proceedings of the National Academy of Sciences. 2019. Vol. 116, No. 46. P. 23209–23215. DOI: https://doi.org/10.1073/pnas.1908221116
8. Drusch M., Del Bello U., Carlier S., Colin O., Fernandez V., Gascon F.,... Bargellini P. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment*. 2012. Vol. 120. P. 25–36. DOI: https://doi.org/10.1016/j.rse.2011.11.026
9. Wulder M. A., Roy D. P., Radeloff V. C., Loveland T. R., Anderson M. C., Johnson D. M.,... Cook B. D. Fifty years of Landsat science and impacts. *Remote Sensing of Environment*. 2022. Vol. 280. 113195. DOI: https://doi.org/10.1016/j.rse.2022.113195
10. Pettorelli N., Safi K., Turner W. Satellite remote sensing, biodiversity research and conservation of the future. *Philosophical Transactions of the Royal Society B*. 2014. Vol. 369, No. 1643. Article 20130190. DOI: https://doi.org/10.1098/rstb.2013.0190
11. Pépin, J. L., Baillieul, S., Bailly, S., & Tamisier, R. (2024). New management pathways for follow-up of CPAP-treated sleep apnoea patients including digital medicine and multimodal telemonitoring. *Thorax*, *80*(1), 52–61. https://doi.org/10.1136/thorax-2024-221422
12. United Nations Environment Programme (UNEP). Carpathians Environment Outlook 2007 (KEO). UNEP/DEWA-Europe, 2007.
13. Turner W., Rondinini C., Pettorelli N., Mora B., Leidner A. K., Szantoi Z., Woodcock C. Free and open-access satellite data are key to biodiversity conservation. *Biological Conservation*. 2015. Vol. 182. P. 173–176. DOI: https://doi.org/10.1016/j.biocon.2014.11.048
14. Hansen M. C., Potapov P. V., Moore R., Hancher M., Turubanova S. A., Tyukavina A., Townshend J. R. G. High-resolution global maps of 21st-century forest cover change. *Science*. 2013. Vol. 342, No. 6160. P. 850–853. DOI: https://doi.org/10.1126/science.1244693
15. Lyalko V. I., Shportiuk Z. M., Patiychuk N. R., Korets M. A. Space monitoring of the environment – An effective mechanism of forest protection. *Ukrainian Journal of Remote Sensing*. 2019. No. 20. P. 4–12. DOI: https://doi.org/10.36023/ujrs.2019.20.145
16. Gorelick N., Hancher M., Dixon M., Ilyushchenko S., Thau D., Moore R. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment. 2017. Vol. 202. P. 18–27. DOI: https://doi.org/10.1016/j.rse.2017.06.031
17. Pepin N., Apple M., Knowles J., et al. Elevation-dependent climate change in mountain environments. *Nature Reviews Earth & Environment*. 2025. DOI: https://doi.org/10.1038/s43017-025-00740-4
18. Kuemmerle T., Hostert P., Radeloff V. C., van der Linden S., Perzanowski K., Kruhlov I. Forest cover change and illegal logging in the Ukrainian Carpathians in the transition period from 1988 to 2007. *Remote Sensing of Environment*. 2009. Vol. 113, No. 6. P. 1194–1207. DOI: https://doi.org/10.1016/j.rse.2009.02.006

Дата першого надходження рукопису до видання: 27.11.2025
Дата прийнятого до друку рукопису після рецензування: 15.12.2025
Дата публікації: 31.12.2025