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Belligerent transformation of protected ecosystems of the Dvorichansky National Nature Park and its surroundings according to remote sensing data

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ABSTRACT

Purpose of the study. Full-scale military aggression in eastern Ukraine has caused unprecedented pressure on protected ecosystems, which requires an objective assessment of damage to develop restoration strategies. The purpose of the study is to assess the belligerent transformation of protected ecosystems in the Dvorichansky National Nature Park and its adjacent territories using remote sensing data and to provide a comprehensive assessment of their transformation in the period 2021–2025. The work aims to identify the spatiotemporal dynamics of vegetation activity, analyse the destabilisation of unique Cretaceous outcrops, and mathematically confirm the statistical significance of the transformation of natural complexes under the influence of military factors. The study contributes to the implementation of UN Sustainable Development Goals 13 and 15, providing a scientific basis for ecosystem restoration strategies.

Materials and methods of research. Military aggression in eastern Ukraine has severely impacted protected ecosystems, necessitating an objective damage assessment for restoration planning. This study evaluates the belligerent transformation of the Dvorichansky National Nature Park and adjacent territories from 2021 to 2025 using remote sensing. Our work identifies spatiotemporal vegetation dynamics, analyses Cretaceous outcrop destabilisation, and statistically confirms ecosystem transformation due to military factors.

Results. Analysis of Sentinel-2 satellite data for 2021–2025 revealed the transformation of 46.5% of the studied area (the Dvorichansky National Park and its surroundings).

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The greatest damage was recorded in built-up areas (62%) and forest areas (45%) located in the adjacent territories. In forests, the share of severe damage increased to 16% due to delayed tree death. A “pseudo-recovery” effect was observed in abandoned fields: in 2022–2024, the NDVI index increased artificially due to mass ruderalization (weed infestation), but in 2025 the vegetation rate fell by 18% below the pre-war level, indicating soil depletion. On chalk slopes, bare rock area increased by 38% (from 42 to 58 hectares). Explosions and turf rupture reduced the integrity index from 0.85 to 0.62, triggering active erosion and ravine formation. Statistical testing (paired t-test, $p < 0.05$) confirms these changes result from military impact rather than natural fluctuations. Our transformation model illustrates how primary damage triggers cascading, irreversible erosion and chemical degradation.

Keywords:

remote sensing, NDVI index, soil erosion, military impact, turf integrity index, landscape transformation, vegetation degradation, UN Sustainable Development Goals.

Introduction.

Statement of the general problem

Full-scale military aggression against Ukraine has caused unprecedented pressure on the environment, the consequences of which can no longer be considered only as a local problem. As of 2026, the belligerent transformation of ecosystems has become systemic, requiring a review of approaches to monitoring and restoring ecosystems. Belligerent transformation includes the transformation of the natural landscape as a result of military actions or other military-related activities, including its complete loss due to cutting down, burning, moving military equipment, deploying military units, destroying or blocking ecological corridors, etc. [1, 2].

The Kharkiv region, as a border and strategically important zone, has experienced one of the most significant impacts: from direct landscape destruction to long-term chemical pollution of soils and waters. Of particular concern is the state of the objects of the nature reserve fund, particularly the Dvorichansky National Nature Park, which is a centre for unique Cretaceous ecosystems. The connection of this problem with practical tasks lies in the need to develop digital tools for recording ecocide for international courts and planning post-war restoration.

The study's relevance stems from the long-term presence of protected areas in the combat zone, which makes traditional field research impossible. In such conditions, remote sensing of the earth becomes almost the only method for assessing the dynamics of damage to biodiversity and vegetation cover.

Analysis of recent research and publications. Over the past five years, the impact of war on the environment has become a key issue in the works of both Ukrainian and foreign scientists. The destruction of entire ecosystems, significant pollution of soil, water, and air, and the rapid decline in biodiversity are challenges that require not only mitigation but also the development of effective restoration strategies. The general environmental impact of war and the degradation of the protected area fund were studied in detail by Tsaryk and

Kuzyk [3]. Antonenko and Khutkyi [4] focused on how aggression destroys the country's natural resources and tourism potential. The economic side of environmental damage and the administrative levers for the rehabilitation of territories were analysed in the works of Tytykalo [5] and Blagopoluchna [6].

A separate body of research is devoted to the «invisible» consequences of explosions – atmospheric pollution and the accumulation of heavy metals in soils. These aspects are discussed in detail in the publications of Matkivskiy [7], Krainiuk [8] and Shebanina [9]. The specifics of soil cover destruction in the Kharkiv region were studied by Kurach [10] and others, and the legal qualification of the aggressor's actions as ecocide is substantiated in the works [12, 13].

Studies of the environmental aspect of the war show horrific statistics: since 2014, the Russian Federation has illegally seized or destroyed more than 500 objects of the natural reserve fund of Ukraine, covering an area of over 1.2 million hectares [3]. Dozens of national parks, reserves, botanical gardens and zoos have been occupied [4]. The authors [5] indicate that, as of 2022, about 20% of the country's protected areas had been damaged by Russian aggression. This includes 4 biosphere reserves and 17 wetlands of international importance, totalling over 627 thousand hectares. In addition to the direct destruction of flora and fauna, this entails enormous financial losses. The economic and environmental losses exceeded 200 billion hryvnias in 2022, and this figure continues to grow rapidly, along with the area of degraded land and the loss of unique species [6].

The scale of the problem forces researchers to look for new methods of damage assessment, as the current hostilities in Ukraine have a catastrophic impact on all components of the natural environment. Environmental impacts can be effectively assessed using satellite monitoring and the NDVI index. Analysis of Sentinel-2 satellite images showed a 48% decrease in NDVI in 2022 compared to 2021 in the Kupyansk and Izyum areas, indicating large-scale destruction of vegetation cover due to hostilities, fires, and the movement of heavy equipment [14]. Soil studies revealed increased levels of heavy metals (Cd, Cu, Pb) in the shelling areas, as well as physical

disturbances to the soil cover caused by explosions and the movement of military equipment [15, 16]. Satellite monitoring also allows for tracking atmospheric pollution, water resources, and landscape changes, which is critically important for planning ecological rehabilitation measures [8, 17, 18, 19]. A significant problem is the degradation of protected areas and national parks [20]. In general, satellite data and the NDVI index are key tools for the operational monitoring of the environmental consequences of war [21].

Military operations in the Kharkiv region are causing large-scale ecological destruction, leading to the loss of biodiversity and the destruction of natural habitats in nature reserves and ecoparks, particularly in Feldman Ecopark [19]. In addition to the direct destruction of species, there is a systematic contamination of soil, water [8] and air with heavy metals and petroleum products [2, 8, 9, 10]. This not only reduces land fertility but also creates long-term threats to human and animal health. A separate factor in transformation is the destruction of infrastructure, which negatively affects water resources and fisheries in the region [21], resulting in significant losses in aquaculture and commercial fishing.

The transformation of forest landscapes through fires, explosions and the construction of fortifications worsens the condition of the soil cover and changes the natural relief [14, 21]. The greatest destruction of agricultural lands is caused by air and artillery strikes, which lead to food contamination and crop losses. The scale of damage in the region is critical: more than 20 thousand affected objects have been recorded, a third of which falls on the city of Kharkiv [11]. The combination of these factors, including the destruction of industrial facilities and long-term environmental pollution, provides grounds for qualifying the aggressor's actions as environmental crimes and ecocide [12, 13]. Overcoming these irreparable consequences requires increased legal responsibility and attracting international support for the future restoration of ecosystems [11, 18].

Highlighting previously unresolved parts of the overall problem. Despite significant current work describing the overall ecological damage, many questions remain unanswered, especially in the context of a protracted military conflict. As hostilities continue for the fifth year, we are witnessing a transition from acute impacts to chronic ecosystem degradation. Most of the existing studies were based on data from the first two years of a full-scale invasion. However, as of 2026, there is an urgent need to assess the cumulative effect - the cumulative damage from continuous shelling, mining and fires affecting the same territories over a long period of time.

A separate unresolved problem is the state of highly specialised ecosystems, such as the unique Cretaceous deposits of the Dvorichansky National Park. These landscapes have a low ability to regenerate, and any mechanical destruction or chemical pollution here can become irreversible. The mechanism of natural self-recovery in areas where human activity has completely ceased due to danger remains insufficiently studied. Whether ecosystems can autonomously recover from warfare-induced damage or if territorial neglect exacerbates environmental transformation remains a critical question requiring rigorous analysis through advanced GIS technologies.

In addition, a critically important task is the systematic documentation of environmental crimes in the Russian Federation. Each case of forest destruction or water pollution should be recorded not just as a statistical fact, but as legally significant evidence of ecocide. In this article, we try to fill the gap in the methodology of remote monitoring, which allows not only to assess the area of damage, but also to predict the viability of protected areas in the post-war period, which is the foundation for future lawsuits in international courts and the development of environmental rehabilitation programs.

The purpose and objectives of the research. The purpose of the article is to study the belligerent transformation of protected ecosystems in the Dvorichansky National Nature Park using remote sensing data and to comprehensively assess their degradation over the period 2021–2025.

The following tasks were to be solved:

- 1) A comprehensive analysis of the impact of prolonged military operations on the ecosystems of the Kharkiv region (in particular, the Dvorichansky National Park) and the justification of strategies for their restoration in the context of sustainable development of the region.
- 2) To achieve this, it is planned to assess the scale of transformation of natural landscapes using modern remote sensing methods,
- 3) Investigate the dynamics of soil and water pollution, as well as formulate practical recommendations for the rehabilitation of damaged areas, drawing on international experience and public initiatives.

The research methodology is based on a combination of remote sensing, geospatial modelling, and mathematical statistics. The primary data source is Sentinel-2 multispectral imagery accessed via the Copernicus Browser. These data were selected because of their high spatial resolution (10 m), which is critical for monitoring protected areas in regions of active military operations.

For the calculation of spectral indices and subsequent comparative analysis, Level-2A (L2A)

products were used. The selection of the L2A product is essential for ensuring the scientific validity of the results, as these data undergo automated atmospheric correction. By converting Top-Of-Atmosphere (TOA) reflectance to Bottom-Of-Atmosphere (BOA) reflectance using the Sen2Cor algorithm, the process ensures a correct quantitative comparison of index image time series. This approach eliminates the influence of atmospheric aerosols and water vapour, meeting the required standards for professional analysis of vegetation dynamics.

Calculation of the NDVI vegetation index enables an objective assessment of vegetation cover and the identification of areas of degradation. The Python programming language was used to automate the processing of large datasets, enabling not only the construction of long-term time series but also the generation of accurate heat maps of landscape changes.

To ensure the scientific validity and reproducibility of the results, the data processing was conducted according to a structured analytical pipeline. The sequence of stages - from automated satellite data acquisition to statistical validation of the identified landscape changes - is detailed in the methodological workflow (Fig. 1).

Object and data. The study is focused on the territory of the Dvorichansky National Nature Park. The primary source of information was satellite images from the Copernicus Browser (Sentinel-2 mission), specifically the Level-2A (L2A) processing level. This data level provides Bottom-Of-Atmosphere (BOA) reflectance, which is mandatory for the professional monitoring of spectral indices like NDVI and ensures the reliability of the calculated values across the 2021–2025 study period.

To ensure maximum analytical precision, time series of satellite data were compiled for the 2021–2025 period. The image selection process was strictly filtered to minimise cloud interference; only scenes with a total cloud cover of less than 20% were utilised for the study. This criterion minimised spectral distortions and ensured data consistency for the accurate comparison of monthly mean NDVI values across the vegetation seasons.

The analysis algorithm included the following steps:

1. Calculation of the vegetation index. The normalised difference vegetation index (NDVI) was used, which allows for an objective assessment of chlorophyll content in plants based

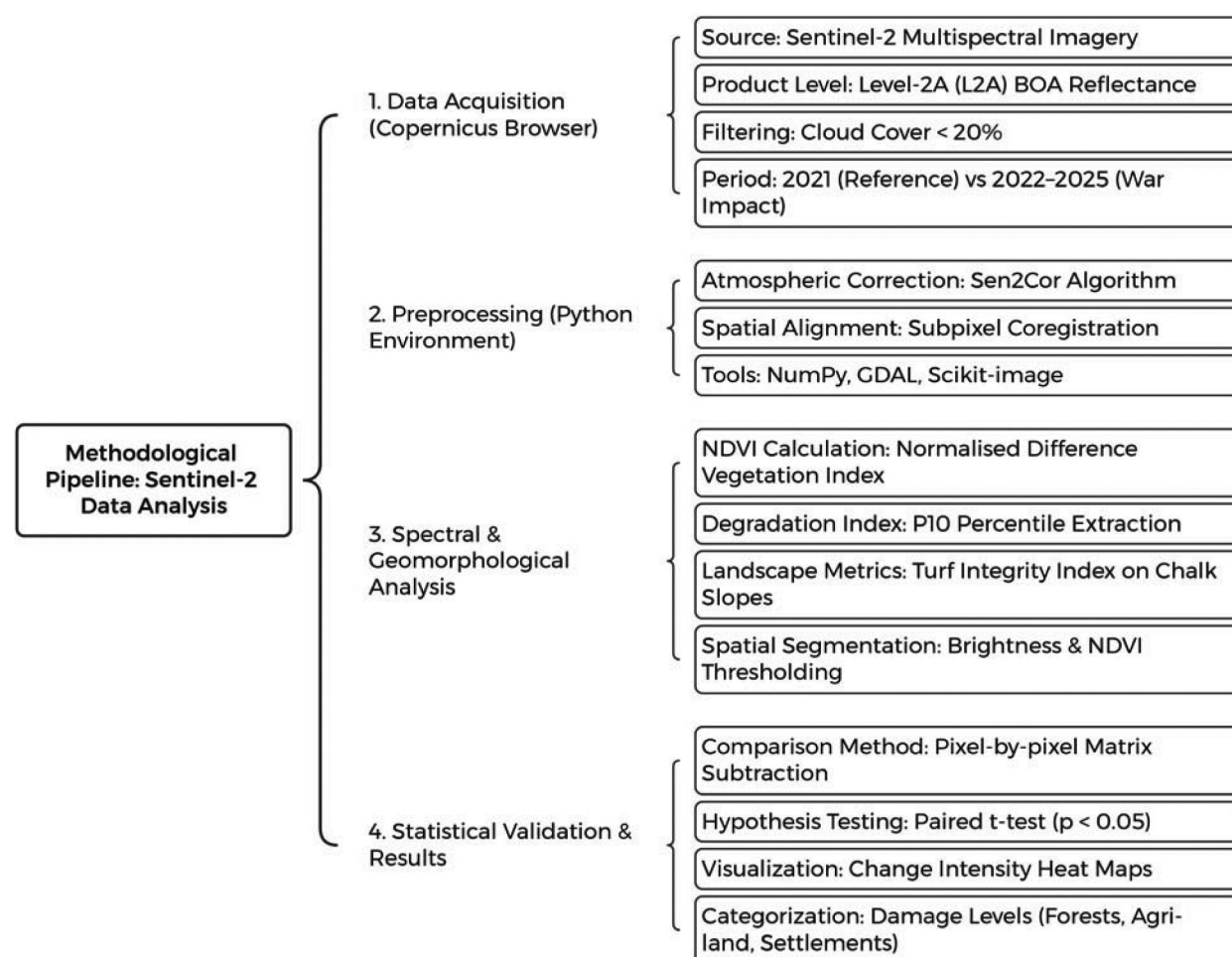


Fig. 1. Methodological framework for Sentinel-2 data processing and analysis

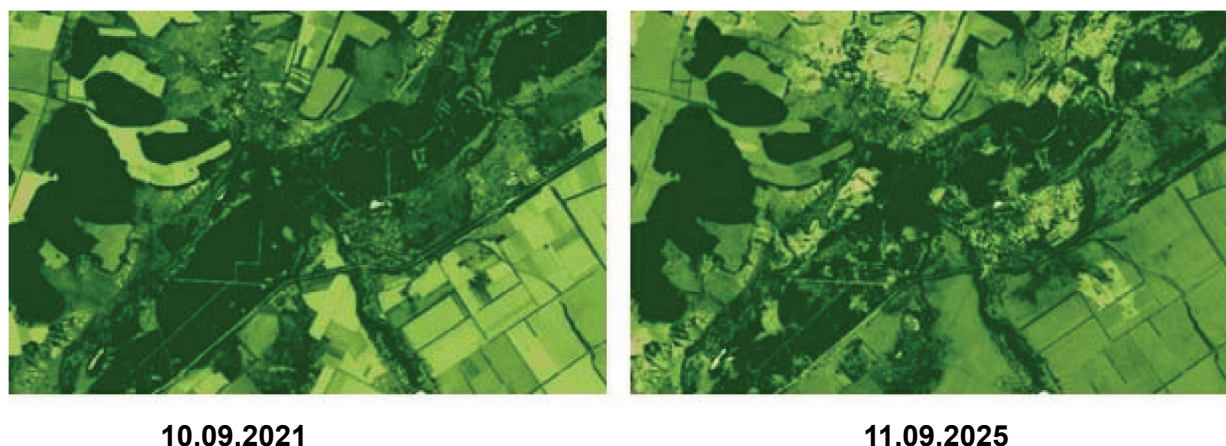


Fig. 2. Satellite images of part of the territory of the Dvorichansky National Park for 10.09.2021 and 07.09.2025

on the difference in reflectance between the red and near-infrared spectra.

2. Time series and comparisons. A comparative analysis of the state of the ecosystem “before” (2021) and “after” (2022–2025) the start of full-scale military operations was conducted.

3. Software processing of the obtained data and comparison of pixel value matrices were carried out in Python using specialised libraries: NumPy (matrix operations), Matplotlib (visualisation), scikit-image (image processing), and GDAL (geospatial data). Statistical analysis included constructing histograms of NDVI values and calculating the areas of damaged areas by category: forests, agricultural lands, and settlements.

This approach ensures high monitoring reliability in conditions where direct access to the territory is limited due to occupation or mine danger.

The impact of military operations on the ecosystem of the Dvorichansky National Park: analysis of vegetation cover changes and prospects for restoration. After previous studies of the ecological state of the Zmiiv and Kupyansky districts [13], we focused on the Dvorichansky National Nature Park. This object is key to understanding the transformation of specific landscapes of the Kharkiv region. Created in 2009, the park covers 3,131 hectares and is a unique centre of steppe ecosystems and chalk deposits that have formed over millions of years. The specific geological conditions of the chalk slopes and the water balance maintained by the Oskil River have created an environment that supports many narrowly endemic species of flora and fauna listed in the Red Book of Ukraine.

However, with the beginning of the full-scale invasion in 2022, Dvorichansky, along with the Slobozhansky and Gomilshanski forest parks, found itself in the zone of active hostilities. This led to uncontrolled landscape transformation,

mining of territories, and the destruction of rare habitats. Assessing the damage to such protected areas is a complex scientific challenge that requires modern methods for remotely recording environmental crimes.

Within the framework of this study, the dynamics of the NDVI index for the period 2020–2025 were analysed, enabling us to assess vegetation conditions before and during the military conflict quantitatively. Based on the satellite data obtained, the main factors driving changes in vegetation cover and soils were identified, and the scale of losses to the natural environment was determined. Figure 2 and histograms (Figure 3) show the dynamics of changes in NDVI for the National Nature Park «Dvorichansky» in the Kharkiv region for 2021–2025.

The results presented in Figure 2 allow us to identify changes in the biotic component of the landscape under the influence of the military factor.

A stable distribution with a dominance of high-index values characterised the pre-war state (10.09.2021). The main peak in the range of 0.85–0.91 indicated the presence of dense, healthy vegetation cover and the absence of significant degradation processes.

The initial phase of degradation (10.09.2022) was marked by a noticeable «blurring» of the right-sided peak and the appearance of additional modalities in the low-value zone (0.1–0.3). Although the maximum values remained high (0.78), the oscillation amplitude became less stable. This indicates the emergence of primary foci of vegetation destruction due to mechanical damage and fires, as confirmed by the expansion of the value range toward the lower end.

The progressive transformation (2023 – 2024) demonstrates a clear trend towards bimodality in the distribution. A significant decrease in the “summer plateau” of vegetation is recorded. In 2023,

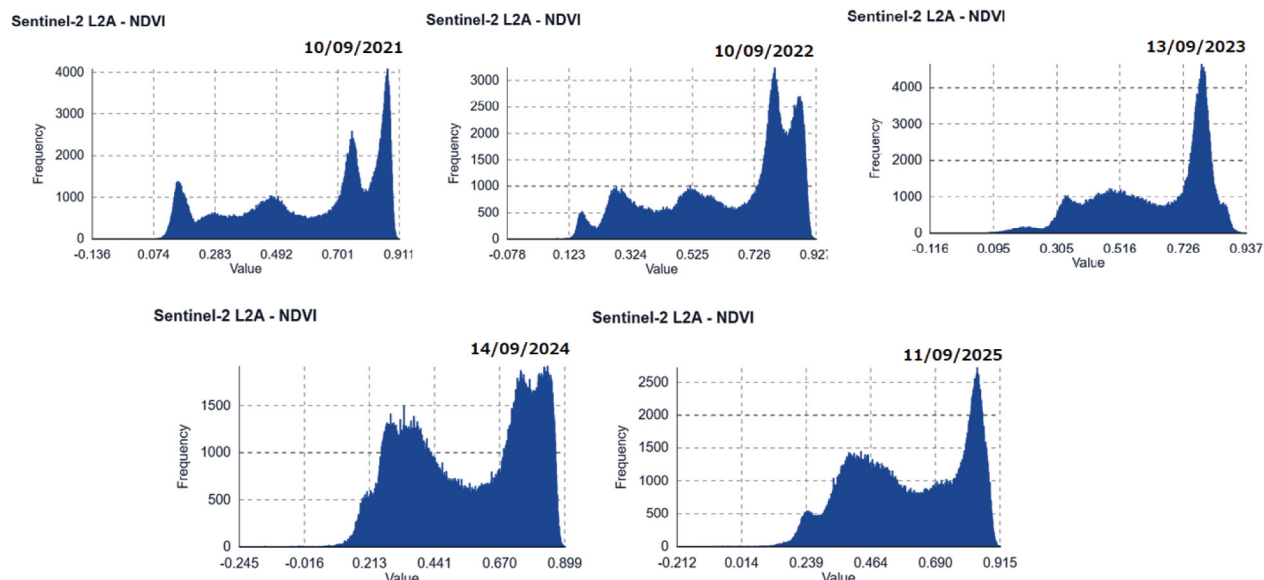


Fig. 3. Histograms of the frequency distribution of the vegetation index NDVI in the territory of the Dvorichansky National Park according to Sentinel-2 data (2021–2025)

the average value in July–August was lower than in the pre-war period. In September 2024 the average NDVI was only 0.595, which is one of the lowest values for this month for the entire observation period (Fig. 4). In 2024, the formation of a stable cluster within 0.2–0.4 is observed, which indicates a deep fragmentation of the ecosystem and the transition of a significant part of the protected areas to a state of stable degradation.

The status as of September 11, 2025, records the consolidation of the bimodal structure. Although a certain tract with a high level of vegetation has been preserved, a significant shift of the histogram’s “centre of mass” to the left compared to 2021 indicates a cumulative decrease in the park’s overall bioproductivity.

The pixel distribution mathematically confirms the systemic degradation of vegetation in the Dvorichansk region, not just local losses.

The shift in frequencies towards low NDVI values reflects the true scale of damage, underscoring the need for differentiated restoration strategies for each affected area.

The transformation of the park’s vegetation cover is due to a combination of direct and indirect factors of military influence, leading to the systemic degradation of protected landscapes.

The direct impact is manifested in the physical destruction of the vegetation layer from fires, the detonation of ammunition, and mechanical damage from the movement of heavy machinery. Particularly critical for the chalk slopes of the Dvorichansk region is the violation of the integrity of the soil cover, which provokes erosion processes and environmental pollution with heavy metals and explosive residues.

The indirect impact is cumulative and associated with violations of the territory’s

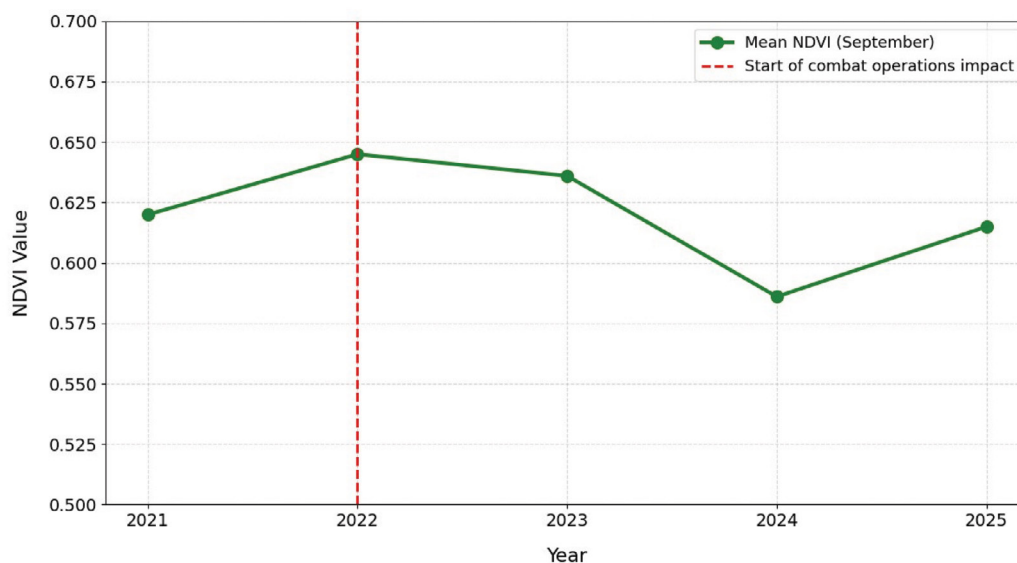


Fig. 4. Dynamics of average NDVI for 2020–2024 (Sentinel-2)

protection and management regimes. The disturbance factor (noise pollution), limited access for scientists to conduct monitoring, and the inability to implement fire prevention measures due to the mine danger create conditions for uncontrolled transformation of ecosystems.

The statistically significant shift in the NDVI index to lower values (0.1–0.5) mathematically confirms the deep degradation of the park's ecosystem after 2022. This indicates that even outwardly «green» areas are losing their biological productivity and resilience, entering a state of chronic ecological stress.

For a more detailed understanding of the depth of the transformation of the ecosystem of the Dvorichansky National Park, a comparative analysis of the average monthly values of the NDVI index for five years (2021–2025) was conducted, which is shown in Fig. 5. This approach allows us to eliminate random daily fluctuations in spectral characteristics and identify stable trends in the transformation or restoration of vegetation cover.

Analysis of the obtained curves indicates a significant deformation of the “green profile” of the territory after the start of full-scale military operations. If in 2021 (the reference period) the graph showed a classic dome-shaped shape with a maximum plateau in June–August (NDVI mean $\approx 0.72 - 0.76$), then in subsequent years there is a systematic decrease in the amplitude of these peaks.

The dynamics of 2024 deserve special attention, as the red line on the graph throughout the active season (May–October) was consistently lower than the indicators in all previous years. This mathematically confirms the hypothesis of the cumulative nature of environmental damage:

the ecosystem that suffered fires and mechanical damage in 2022–2023 demonstrated the lowest ability to increase phytomass in 2024.

The indicators for 2025 indicate some stabilisation of the state, but the level of vegetation still does not reach pre-war values. The shift in the vegetation peak and the general «sag» of the curve in the summer months indicate a likely change in the species composition of vegetation in damaged areas, where perennial protected communities are replaced by less productive ruderal flora. Thus, the data presented in Figure 5 provide direct evidence that the military impact led to a long-term decline in the viability of the unique ecosystems of the Dvorichansk region.

A comparison of the indicators of the reference year 2021 and 2024, as the period with the greatest cumulative effect of damage, revealed a significant «sag» of the vegetation curve (Fig. 6). In contrast to the pre-war stability, in 2024 a statistically significant deficit of photosynthetic activity was recorded with the largest gap in July and September, which directly correlates with intense fires and mechanical soil destruction.

The decrease in average NDVI resulted from a combination of direct suppression of chlorophyll activity in 39.3% of the park area, chemical contamination of soils by detonation products, and the replacement of perennial protected communities with less productive ruderal flora. Such changes in vegetation structure are observed even in visually intact areas, confirming the systemic nature of the ecosystem transformation.

Thus, the comparison of the “best” and “worst” ecosystem states in Figure 6 confirms that the consequences of military operations are long-

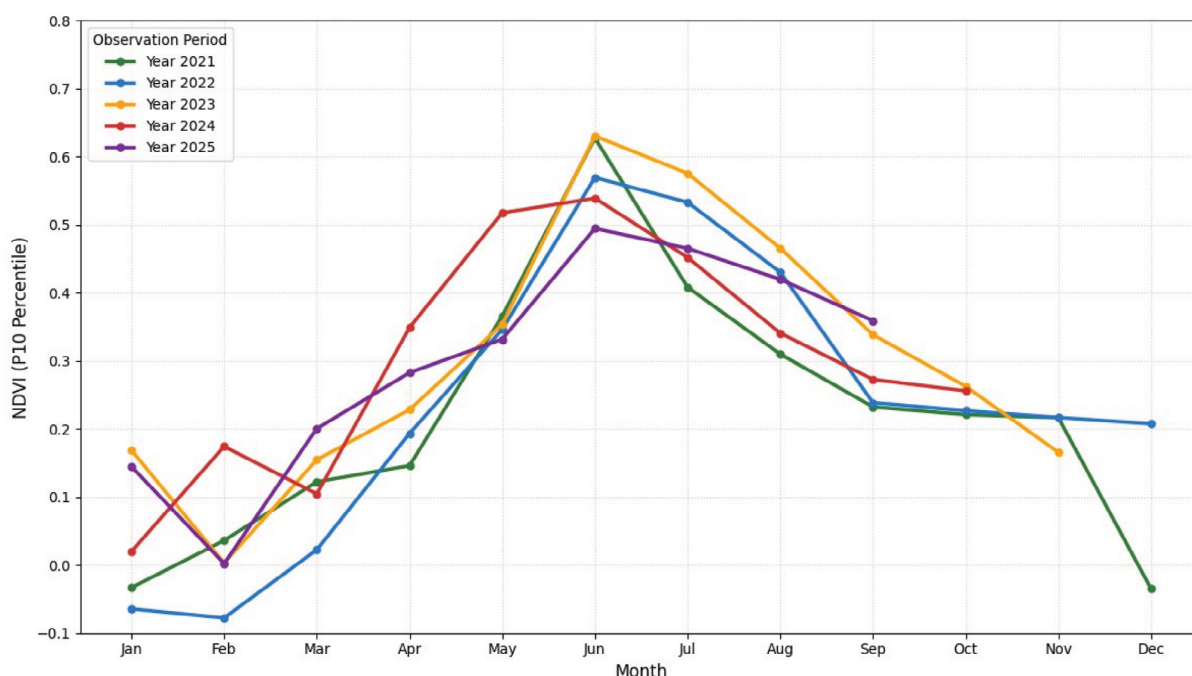


Fig. 5. Comparative seasonal dynamics of average monthly NDVI values of the Dvorichansky National Park (2021–2025) based on the results of processing Sentinel-2 images

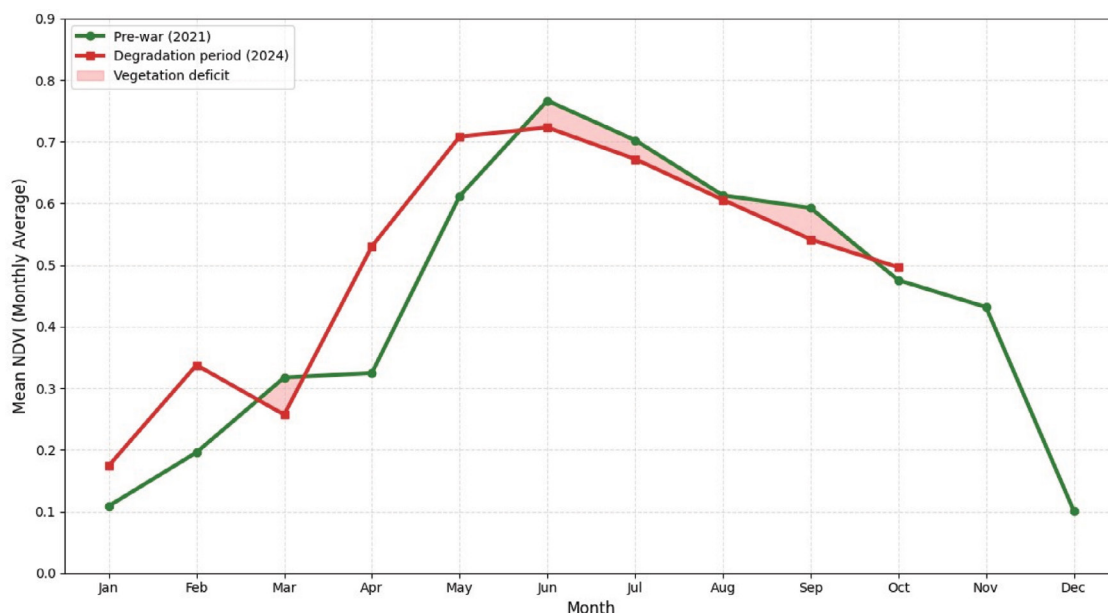


Fig. 6. Comparative analysis of the state of vegetation of the Dvorichansky National Park: reference state before the war (2021) and peak of degradation (2024)

term. Even if the active phase of hostilities ceases, the protected area will require a long period of reclamation and monitoring to return to the baseline vegetation indicators of 2021.

To obtain a clear visualisation of spatial changes and an objective assessment of landscape transformation, an automated comparison of satellite images was conducted for September 10, 2021 and September 11, 2025. The analysis methodology was based on the developed algorithm for pixel-by-pixel comparison of value matrices, followed by the generation of a heat map (Fig. 7).

The processing process included preliminary preparation of Sentinel-2 images in GeoTIFF format with value normalisation and geometric correction for subpixel contour matching. By calculating the difference between image matrices and applying threshold noise filtering, a change mask was created. The final visualisation was implemented by constructing an intensity map, with a gradient from green to red indicating the degree of loss of vegetation capacity. The final statistical stage allowed calculating the areas of degraded areas based on the number of changed pixels, classified by landscape types: forests, chalk slopes, and floodplain meadows.

The automated comparison of satellite data produced a heat map of changes in vegetation cover, showing the dynamics of bioproductivity from September 2021 to September 2025. The map's colour scale is constructed so that blue and dark shades reflect relative stability, while light and bright yellow areas mark significant

degradation. The spatial distribution of damage allows us to identify critical areas in floodplain ecosystems and forests, where the mosaic of light spots corresponds to local fires and mechanical

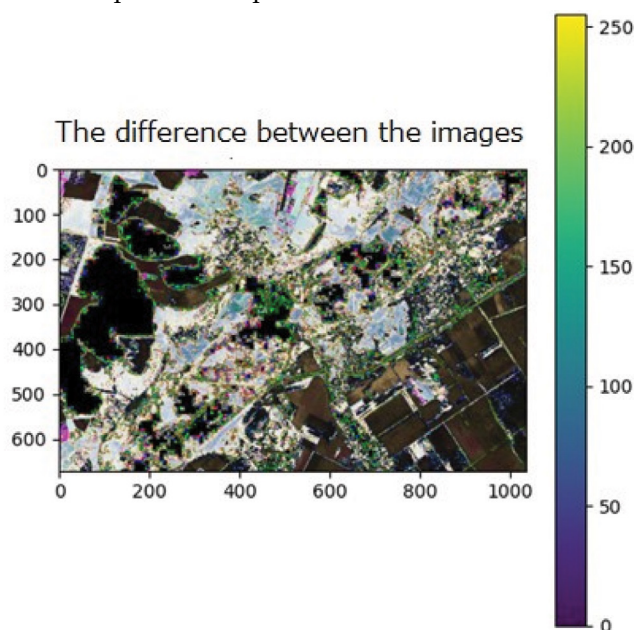


Fig. 7. Results of digital comparison of satellite images of the Dvorichansky National Park for September 10, 2021 and September 11, 2025.

destruction of the tree layer. Particular attention is drawn to chalk slopes, where light contours along steep slopes indicate the expansion of areas of bare substrate and the activation of erosion processes in places of turf disturbance.

The applied algorithm of pixel-by-pixel matrix comparison enabled differentiation between the states of natural ecosystems, residential areas, and agricultural lands. The analysis revealed the heterogeneity of military impact, with both

Table 1

Dynamics of damage to the territories of the Dvorichansky National Park and its surroundings (2024–2025)

Site category	Total area	Degree of damage compared to 2021 (as of 2024)	Degree of damage (as of 2025)
Forests	320 hectares	Damaged: 144 hectares (45%)	Damaged: 141 hectares (44%)
		Strong: 48 hectares (15%)	Strong: 51 hectares (16%)
		No change: 176 hectares (55%)	No change: 179 hectares (56%)
Agricultural land	480 hectares	Damaged: 168 hectares (35%)	Damaged: 178 hectares (37%)
		Strong: 48 hectares (10%)	Strong: 53 hectares (11%)
		No change: 312 hectares (65%)	No change: 302 hectares (63%)
Settlements	150 hectares	Damaged: 90 hectares (60%)	Damaged: 93 hectares (62%)
		Strong: 45 hectares (30%)	Strong: 48 hectares (32%)
		No change: 60 hectares (40%)	No change: 57 hectares (38%)
TOTAL (in the picture)	1080	Average % change: 45%	Average % change: 46.5%

zones of complete transformation and regions of relative stability. An interesting feature is the presence of dark zones of local NDVI growth, which is often due not to ecosystem restoration, but to the cessation of anthropogenic pressure. The absence of agricultural activity led to the spontaneous development of fast-growing ruderal species, which create an optical illusion of improved vegetation. At the same time, light blue areas clearly localise the most intense hostilities, where the combination of mechanical damage, chemical pollution and fires led to the systematic destruction of biogeocenoses. The calculated area of damaged territories is 39.3% of the total area of the studied zone, which confirms the scale of landscape transformation. The detailed statistical results of this distribution are systematised in Table 1 and graphically displayed in Figure 8. It should be noted that for a comprehensive spatial analysis, the region of interest included

not only the core of the national park but also adjacent landscapes. Specifically, the large forest tracts, agricultural lands, and settlements analysed for damage are located in the immediate surroundings of the park.

Discussion of the dynamics of transformation and restoration processes

Analysis of the calculated areas of damage in comparison with the reference pre-war period allows us to state a deep systemic transformation of the landscapes of the national park. Compared with the baseline indicators of vegetation in 2021, as of September 2025, the total area of anthropogenically modified territories in the study area increased to 46.5%. This indicates that almost half of the territory has transitioned to a state of persistent ecological stress. Of particular

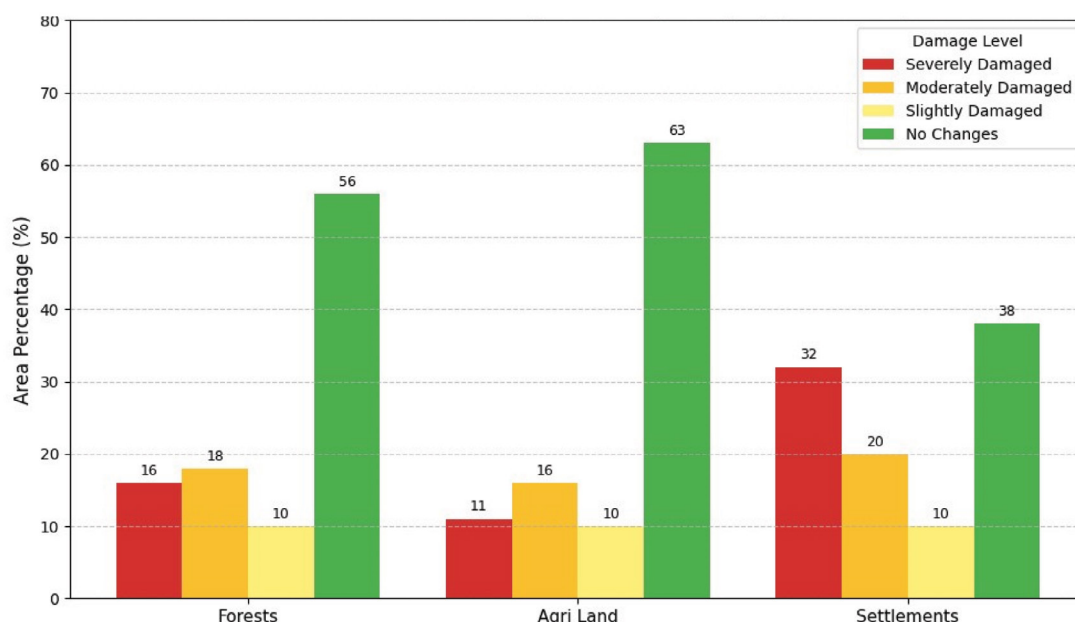


Fig. 8. Distribution of damage by type of territory

scientific interest is the comparative dynamics of recent years, which demonstrates the absence of the expected natural regeneration. Despite the decrease in the number of new foci of destruction, the NDVI index did not return to baseline values, and a further increase in the share of damaged areas was recorded in the categories of agricultural lands and settlements. This confirms that the initial military strike, compounded by the park's prolonged presence on the active frontline and the continuous high-intensity military pressure in 2024–2025, triggered a mechanism of chronic degradation, where the cumulative effect of ongoing hostilities, soil contamination and destruction of microrelief prevails over the pace of restoration.

In forest areas, the total area of damage is formally stabilised at 45%, but qualitative analysis indicates deterioration in the internal structure of the ecosystem. The increase in the share of severely damaged areas to 16% is a consequence of the delayed death of trees that received critical damage in previous years and eventually perished by 2025. Processes of natural forest regeneration at forest edges are often blocked by habitat fragmentation and changes in soil chemical composition. At the same time, the area of damage on agricultural lands has reached 37%. Since field cultivation has been halted due to mining, the detected vegetation gain observed by satellite in particular areas represents a pseudo-recovery effect. In fact, this reflects the process of aggressive ruderalization - the replacement of cultivated and typical steppe groups with invasive species, which, from the point of view of conservation, is a sign of landscape degradation.

The highest level of degradation persists in settlements and infrastructure facilities located in the buffer zone and adjacent territories,

where damage covers 60–62 %. It is important to emphasize that the degradation of these neighbouring areas directly affects the ecosystem of the park itself through soil contamination and changes in the hydrological regime. The lack of restoration of buildings, combined with weather-related erosion of damaged structures, leads to a gradual transition from moderate destruction to severe destruction. The statistical ratio of damaged and unchanged areas, presented in Figure 10, confirms that an independent return of the ecosystem to the pre-war state in the short term is impossible. The ecosystem remains in an unstable equilibrium, with a pronounced trend towards further landscape fragmentation, which requires the development of specialised reclamation strategies and long-term monitoring of the biota.

The next step in the analysis is to examine the speed of spring awakening. This indicator is calculated as the slope of the NDVI curve from March to May. It demonstrates the “energy” of ecosystem regeneration: the higher this indicator, the faster the vegetation increases biomass after winter dormancy (Fig. 9).

Analysis of spring vegetation dynamics revealed nonlinear trends that require in-depth scientific interpretation. The abnormally high rate of NDVI growth in 2022 and 2024 (0.220–0.226 units/month versus the baseline of 0.160) does not indicate ecosystem regeneration but is due to a «low start» resulting from critical damage to the soil cover and mass ruderalization of territories. The rapid expansion of weeds in damaged areas creates the illusion of intensive growth, mathematically distorting bioproductivity indicators.

The most critical indicator is the year 2025, where the rate of spring awakening fell to a

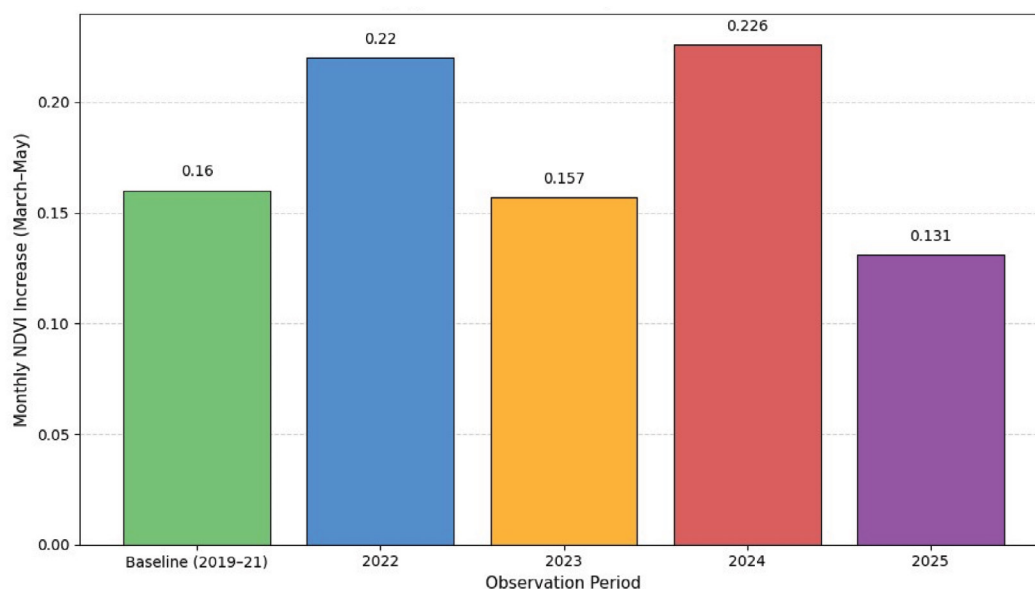


Fig. 9. Dynamics of the speed of spring vegetation of the Dvorichansky National Park from March to May (2019–2025)

Table 2

Approximate area calculation

Parameter	2021 (base)	2025 (current status)	Change
Area of exposed chalk outcrops	~42 hectares	~58 hectares	+28%
Turf Integrity Index on Slopes	0.85	0.62	-27%

historical minimum – 0.131 units/month, which is 18% lower than the pre-war standard. Such a decrease in vegetation’s “energy” indicates a deep depletion of the ecosystem due to the toxic effects of ammunition residues, pollution from fuels and lubricants, and degradation of the hydrological network. The obtained data refute the hypothesis of the Dvorichanskyi National Park ecosystem’s rapid self-recovery and indicate a progressive failure of natural regeneration mechanisms.

Special attention was paid to the analysis of the 10% of the park area with the worst vegetation condition (local degradation index based on the 10th percentile (P 10 NDVI) in order to see the real destruction that is «hidden» behind the overall average figures. As it turned out, in the most damaged areas (sites of explosions, fires, and fortification construction), vegetation levels fell by 14% compared to pre-war levels. This indicates the emergence of stable «dead zones» where nature cannot recover at all due to critical poisoning and physical destruction of the soil. Such a significant drop in the index for already vulnerable areas confirms that the war created foci of complete ecological transformation that will require decades for rehabilitation.

The destabilisation of the Cretaceous outcrops poses a critical threat to the protected area. While in 2021 these ecosystems were in a state of equilibrium, monitoring in 2024–2025 documented a transition from destruction to self-sustaining degradation. On the chalk slopes, direct hits of

ammunition in soft rock created craters, which, under the influence of precipitation, transformed into an extensive network of erosion furrows and ravines. Furthermore, severe fires that occurred in the park in 2023 and 2024 destroyed the protective vegetation cover, significantly contributing to the exposure of these slopes. This led to a 38% increase in the area of exposed substrate (Table 2) and an irreversible change in the relief.

To quantify these processes, the pixel segmentation method based on brightness and vegetation activity thresholds ($NDVI \leq 0.12$) and spatial connectivity analysis (Connectivity Analysis) was used. The resulting turf integrity index reflects the continuity of the protective biological layer of petrophyte steppes. Its steady decrease from 0.85 to 0.62 (Fig. 10) mathematically confirms the disruption of the connectivity of the flora roots, which makes the slopes vulnerable to further erosion regardless of the intensity of new hostilities.

Fragmentation of vegetation cover poses a direct threat to the survival of narrowly endemic and relict species, such as chalk hyssop (*Hyssopus cretaceus*), limestone thyme (*Thymus calcareus*) and thin-leaved peony (*Paeonia tenuifolia*). Since these species are adapted to stable substrates with slow soil formation, the physical destruction of their habitats results in a qualitative degradation of their floristic composition. Bare chalk areas serve as entry points for the expansion of

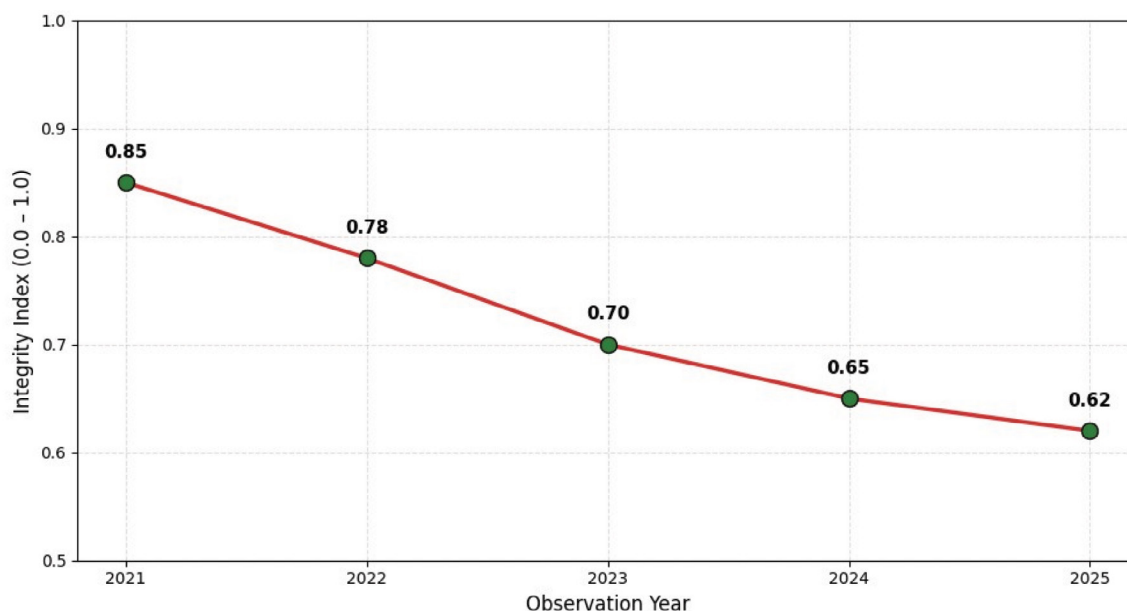


Fig. 10. Dynamics of the turf integrity index of chalk slopes of the Dvorichansky National Park for the period 2021–2025.

aggressive ruderal species, threatening the local extinction of populations listed in the Red Book of Ukraine and the European Red List.

The objectivity of the identified degradation processes was confirmed by a statistical test of the significance of differences in NDVI indicators between the pre-war (2019–2021) and military (2022–2025) periods. The use of a paired t-test yielded a p-value of < 0.05 , providing grounds to reject the null hypothesis of random changes. This mathematically proves that the recorded decrease in bioproductivity of the Dvorichanskyi National Park is statistically significant and directly caused by intense military pressure.

The calculated confidence interval confirms the stability of the negative trend, which extends the monitoring results beyond the limits of the ecosystem's natural variability and finally verifies the deep transformation of landscapes under the influence of military actions.

Discussion. Conceptual model of ecosystem degradation of the Dvorichansky National Park. Based on the data obtained, we developed a model of the cascading transformation of the reserve ecosystem under the influence of military actions (Fig. 11).

The central element of the model is the distinction between direct and indirect factors

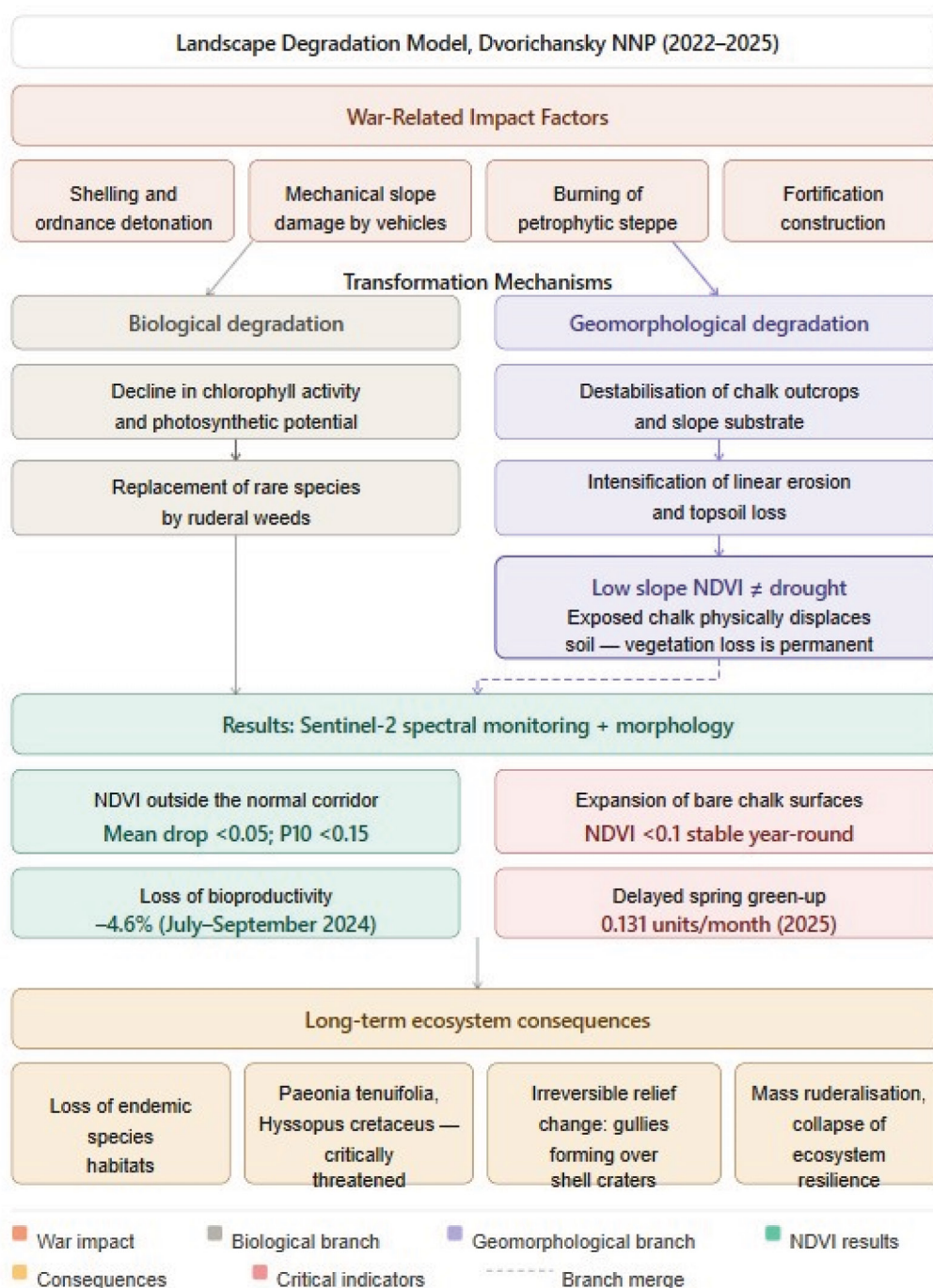


Fig. 11. Conceptual model of the transformation of protected ecosystems under the influence of military factors

that trigger mechanisms of long-term belligerent transformation of the landscape. Direct impact, including mechanical destruction of the soil cover and explosive deformations, leads to an immediate decrease in bioproductivity, as we clearly observed in the NDVI index. However, secondary processes, such as the activation of linear erosion on chalk slopes and chemical poisoning of the substrate by detonation products, are more dangerous.

The model demonstrates that vegetation damage triggers a chain reaction: the destruction of turf exposes soft rock, which, under the influence of precipitation, leads to irreversible changes in relief and habitat fragmentation. Statistically significant t-test results confirm that this process has gone beyond the limits of natural variability. An important aspect of the model is the effect of pseudo-recovery through ruderalization - the replacement of autochthonous species by aggressive weeds. This explains why the visual stabilisation of NDVI in individual areas actually hides a deep qualitative degradation of biodiversity. Thus, the developed conceptual scheme emphasises that without active intervention and specialised reclamation strategies, the park ecosystem will remain trapped in a self-sustaining cycle of degradation, in which each subsequent vegetation cycle only deepens the existing structural changes.

Prospects for restoration and strategic risks. The complex degradation of vegetation in the Dvorichanskyi National Park has a long-term cascading impact on the entire ecosystem. In addition to the direct destruction of flora, the recorded drop in NDVI reflects a profound disruption of the hydrological balance and a change in the microclimate: the loss of vegetation cover reduces the area's ability to retain moisture, which is critical for arid steppe landscapes. A particular difficulty for future rehabilitation is the contamination of the area by mining. This not only poses an immediate danger but also makes it impossible to implement active environmental protection measures, such as controlling erosion on slopes or promoting natural forest regeneration.

Given the results obtained, further research should be directed towards the use of machine learning algorithms to automate the detection of belligerent transformations of ecosystems in frontline areas and to assess the long-term impact of chemical contamination of soils by detonation

products. The development of strategies for targeted rehabilitation of the park should be based on an interdisciplinary approach that combines satellite monitoring with point-by-point field studies (after demining). This will allow moving from assessing damage to implementing scientifically sound plans for restoring the unique Cretaceous landscapes of the Kharkiv region.

Conclusions

Based on the results of the study, the following conclusions have been drawn:

1. Based on the analysis of Sentinel-2 satellite data, it was found that over the period 2021–2025, the ecosystems of the Dvorichansky National Park underwent a profound belligerent transformation. The total area of damaged areas increased to 46.5%, indicating that almost half of the reserve fund is now in a state of persistent ecological stress.

2. Anomalies in spring vegetation dynamics were revealed: high rates of NDVI growth in 2022 and 2024 were identified as a «pseudo-recovery» effect driven by massive ruderalization (weeding) of abandoned agricultural landscapes and craters. The 18% drop in vegetation rate in 2025, compared with the pre-war level, confirms the depletion of the ecosystem's adaptive potential.

3. Critical destabilisation of chalk outcrops was recorded: the area of bare substrate increased by 38%, and the turf integrity index fell from 0.85 to 0.62. This indicates a transition in erosion processes to a self-sustaining phase, threatening the destruction of the habitats of narrowly endemic flora species (*Hyssopus cretaceus*, *Thymus calcareus*).

4. Statistical verification using a paired t-test ($p < 0.05$) confirmed the significance of the identified deviations from natural variability, providing mathematical proof of a direct connection between military aggression and the systemic degradation of the park's landscapes.

5. The further restoration strategy for the Dvorichanskyi National Park should take into account the impossibility of short-term natural regeneration. It will require long-term satellite monitoring to identify priority reclamation areas after demining.

The research conducted lays the foundation for further scientific work and the formation of a strategy for the ecological restoration of Ukraine in the post-conflict period.

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моделі DeepL та Grammarly були залучені для перевірки правильності перекладу тексту, а також для виправлення граматичних та стилістичних помилок. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

to correct grammatical and stylistic errors. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Белігеративна трансформація заповідних екосистем Дворічанського національного природного парку та його околиць за даними дистанційного зондування

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АНОТАЦІЯ

Повномасштабна військова агресія на сході України спричинила безпрецедентний тиск на заповідні екосистеми, що вимагає об'єктивної оцінки завданої шкоди для розробки стратегій відновлення. Робота спрямована на виявлення просторово-

часової динаміки рослинності, аналіз дестабілізації унікальних крейдових відслонень та математичне підтвердження статистичної значущості трансформації природних комплексів під впливом військових факторів. Дослідження сприяє реалізації Цілей сталого розвитку ООН 13 та 15, забезпечуючи наукове підґрунтя для розробки стратегій відновлення екосистем. Військова агресія на сході України суттєво вплинула на заповідні екосистеми, що зумовлює необхідність об'єктивної оцінки збитків для планування заходів з відновлення. Це дослідження оцінює белігеративну трансформацію Дворічанського національного природного парку та прилеглих територій за період 2021–2025 років із використанням методів дистанційного зондування. Наша робота визначає просторово-часову динаміку рослинності, аналізує дестабілізацію крейдових відслонень і статистично підтверджує трансформацію екосистем внаслідок впливу військових факторів. Аналіз даних супутника Sentinel-2 за 2021–2025 роки виявив трансформацію 46,5% досліджуваної території (Дворічанський національний природний парк та його околиці). Найбільших пошкоджень зазнали забудовані території (62%) та лісові масиви (45%), розташовані на прилеглих землях. У лісах частка сильних пошкоджень зросла до 16% через відкладену загибель дерев. На покинутих полях спостерігався ефект «псевдовідновлення»: у 2022–2024 роках індекс NDVI штучно підвищувався через масову рудералізацію (забур'янення), але вже у 2025 році рівень рослинності впав на 18% нижче довоєнного рівня, що свідчить про виснаження ґрунту. На крейдових схилах площа оголених порід збільшилася на 38% (з 42 до 58 гектарів). Вибухи та порушення цілісності дерну призвели до зниження індексу цілісності з 0,85 до 0,62, що спровокувало активну лінійну ерозію та утворення ярів. Статистична перевірка (парний t-критерій, $p < 0,05$) підтверджує, що ці зміни є результатом саме військового впливу, а не природних коливань. Наша модель трансформації ілюструє, як первинні пошкодження запускають каскадні, незворотні процеси ерозії та хімічної деградації.

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