Chapter 12

ENVIRONMENTAL CONSEQUENCES OF MILITARY OPERATIONS IN UKRAINE ON THE EXAMPLE OF THE KHARKIV REGION[1]

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INTRODUCTION

The current military operations on the territory of Ukraine have a large-scale impact on the natural environment. The destruction of ecosystems, soil, water and air pollution and biodiversity decline pose serious environmental challenges. Research into the effects of military operations on Ukraine's ecosystem is important for developing effective restoration measures and sustainable management of natural resources.

Numerous studies show that the hostilities in Ukraine have caused significant damage to protected areas, including national parks, through pollution, destruction of flora and fauna, and occupation. Other studies emphasize the need to restore these areas and bring the aggressor to justice.

The study of the environmental aspect of the Russian-Ukrainian war found that since 2014, the Russian Federation has illegally seized and destroyed more than 500 objects of the nature reserve fund of Ukraine, with a total area of more than 1.2 million hectares[2]. Dozens of national nature parks, regional landscape parks, nature reserves, botanical and dendrological gardens, zoological parks and other protected areas have come under occupation[3].

[1] This project was supported by Documenting Ukraine, a project of the Institute for Human Sciences, IWM Vienna

[2] Царик Л., Кузик І. Російсько-українська війна: природоохоронний аспект. *Наукові записки Тернопільського національного педагогічного університету імені Володимира Гнатюка. Сер. Географія*. 2022. №2. С. 100-106. DOI:10.25128/2519-4577.22.2.13

[3] Антоненко В., Хуткий В. Вплив російської військової агресії на природні туристичні ресурси України. *Вісник Київського національного університету культури і мистецтв. Серія: Туризм*. 2022. 5(1). С. 64-82. DOI:10.31866/2616-7603.5.1.2022.262003.

The authors[4] examine the damage to protected areas, pointing out that about 20% of the area of all state protected areas in Ukraine, including 17 internationally important wetlands with a total area of 627,300 hectares and four biosphere reserves in 2022, was damaged as a result of Russian aggression.

According to the authors[5], Russia's invasion of Ukraine has led to significant losses for the economy and the environment, including a reduction in protected areas and unique species of flora and fauna, as well as destruction, the amount of which exceeded UAH 200 billion in 2022.

The hostilities in the Kharkiv region of Ukraine are causing significant environmental destruction, affecting biodiversity, natural resources and land cover. The main consequences include the following aspects:

1. Loss of biodiversity and destruction of natural areas such as nature reserves and eco-parks. This includes the destruction of several animal and plant species, as well as the destruction of their natural habitats. Threats to ecosystems and biodiversity, in particular, in the example of damage in Feldman Ecopark, were studied by the study's authors[6].

2. Pollution of soil, water[7] and air. Pollutants include heavy metals[8] and oil products that negatively affect soil fertility and threaten human and animal health[9]. Water resources also suffer from pollution, with increasing concentrations of sulphates and ammonium nitrogen. Air pollution, although less intense, also occurs in the region.

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[4] Tytykalo, R., Pavlovska, N., Andriiets, M. Economic and administrative methods of restoration by local governments of the environment of Ukraine destroyed as a result of military operations. *Baltic Journal of Economic Studies*. 2022. 8(5). С. 184–190. DOI:10.30525/2256-0742/2022-8-5-184-190.

[5] Благополучна, А., Ляховська, Н., Парахненко, В. Екологічні та економічні збитки від повномасштабного військового вторгнення росії в Україну. *Горизонти економіки*. 2022. 3(21). С. 53–61. DOI:10.31499/2616-5236.3(21).2022.263572.

[6] Kucher, A., Honcharova, A., Kucher, L., Bieloborodova, M., & Bondarenko, L. Impact of War on the Natural Preserve Fund: Challenges for the Development of Ecological Tourism and Environmental Protection. *Journal of Environmental Management and Tourism.* 2023. Issue 5(69). P. 2414-2425. DOI:10.14505/jemt.v14.5(69).23.

[7] Matkivskyi, M., Taras, T. Pollution of the atmosphere, soil and water resources as a result of the Russian-Ukrainian war. *Екологічна безпека та збалансоване ресурсокористування*. 2024. 15(1). С. 87-99. DOI:10.69628/esbur/1.2024.87.

[8] Krainiuk O. V., Buts Y. V., Didenko N. V., Barbashyn V. V. Ecological Consequences of Environmental Pollution with Heavy Metals as a Result of the War in Ukraine. *European Association of Geoscientists & Engineers. 17th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment,* Nov. 2023, Vol. 2023. P. 1–5. DOI: 10.3997/2214-4609.2023520013.

[9] Shebanina, O., Kormyshkin, I., Bondar, A., Bulba, I., Ualkhanov, B. Ukrainian soil pollution before and after the Russian invasion. *International Journal of Environmental Studies*, 2023. 81(1). P. 208 – 215. DOI:10.1080/00207233.2023.2245288.

3. Damage to forest landscapes due to fires caused by explosions and felling of trees for the construction of fortifications. Such actions lead to degradation of soil cover and changes in the topography. Military activities significantly impact agricultural land and soil cover–aviation and artillery cause the most damage. Pollution of soil, water and air leads to crop losses, food contamination and threats to human health. Over 20,000 facilities have been damaged in the region, with 31% of them located in Kharkiv[10].

4. Economic losses in the fisheries sector. Military operations affect the state of aquatic bioresources, which negatively affects the fisheries sector. This leads to losses in aquaculture and commercial fishing.

5. Actions related to military operations can be qualified as environmental crimes and ecocide. These include the destruction of industrial facilities and environmental pollution, which has long-term and irreparable consequences for the region's ecosystems[11].

The hostilities in the Kharkiv region are leading to large-scale ecosystem destruction, including loss of biodiversity, pollution of natural resources and land degradation. To overcome these challenges, it is necessary to take urgent measures to restore the environment, strengthen responsibility for its protection and engage the international community in addressing the environmental ecocide in the region[12].

The purpose of the study is to examine the impact of hostilities on the ecosystem of Ukraine in terms of sustainable regional development, to analyse environmental risks and to propose practical solutions to minimise their consequences in restoring the natural environment and ensuring sustainable development.

The objectives of the article include analysing the primary sources of environmental pollution caused by military operations, assessing their impact on soil, water, atmosphere and biodiversity, as well as studying the role of society and international organisations in restoring ecosystems and offering recommendations for improving the environmental situation on the way to sustainable development of Ukraine's regions.

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[10] Курач, Т., Коренець, О., Литвиненко, Н., Підлісецька, І. Деградація ґрунтового покриву в Харківській області внаслідок військових дій. *Вісник Київського національного університету імені Тараса Шевченка. Військово-спеціальні науки*. 2023. 4(56). С. 50-56. DOI: 10.17721/1728-2217.2023.56.50-56.

[11] Кузьменко В.О., Третяк Н.М., Чорнай В.І., Яриш І.Ю. Воєнний екоцид в Україні як згубний наслідок застосування російських ракет та снарядів. *Наукові праці Державного науково-дослідного інституту випробувань і сертифікації озброєння та військової техніки*. 2024. 1(19). С. 62–72. DOI:10.37701/dndivsovt.19.2024.08.

[12] Токарчук Д. Екозлочини та проблеми відходів під час воєнних дій в Україні. *Наукова думка: Економіка і менеджмент*. 2022. 3(79). С. 146–154. DOI:10.32782/2521-666x/2022-79-21

1. Infrastructure and facilities affected by hostilities

The impact of hostilities on Ukraine's ecosystem is directly related to the economic and social importance of the affected regions (fig. 1). Ukraine is key in the global markets for agricultural products, metallurgy, energy, and other industries. The regions that have suffered the most damage are of strategic importance due to their agricultural, industrial, and transport infrastructure development. Fertile soils ensure food security, industrial enterprises are vital sources of income, and transport routes and ports facilitate economic interaction with other countries.

The social significance of the Kharkiv region lies in the provision of jobs, the stability of local communities and the satisfaction of basic needs. The destruction of the affected regions leads to a decline in economic activity and a deterioration in living conditions. The hostilities have led to significant losses among infrastructure facilities:

– Industrial enterprises: destruction of plants and factories, contamination of territories with toxic substances.

– Transportation infrastructure: damage to railways, roads, bridges and ports, which complicates logistics and evacuation.

– Energy facilities: destruction of power plants, transformer substations and gas pipelines causes energy crises.

– Social facilities: damage to schools, hospitals, and residential buildings creates a humanitarian catastrophe.

– Environmentally critical facilities: water treatment plants, fuel storage tanks, and protected areas have suffered significant losses.

These losses exacerbate the long-term environmental degradation and complicate efforts to restore the region (Figure 1).

The destruction of infrastructure causes economic losses and has long-term environmental and social consequences that require a comprehensive approach to address.

Military operations on the territory of Ukraine have caused significant damage to the natural environment, polluting soil, water resources, and the atmosphere with toxic substances, fuels, lubricants, and chemicals.

It also leads to the degradation of natural landscapes, a decrease in biodiversity and disruption of ecosystems. In addition, the threat of mines and the destruction of infrastructure make it difficult to restore and monitor the environment, which worsens the population's living conditions.

The hostilities are causing long-term negative impacts on Ukraine's ecological system. Restoring the environment requires significant efforts, resources and international cooperation to minimise damage and ensure sustainable development.

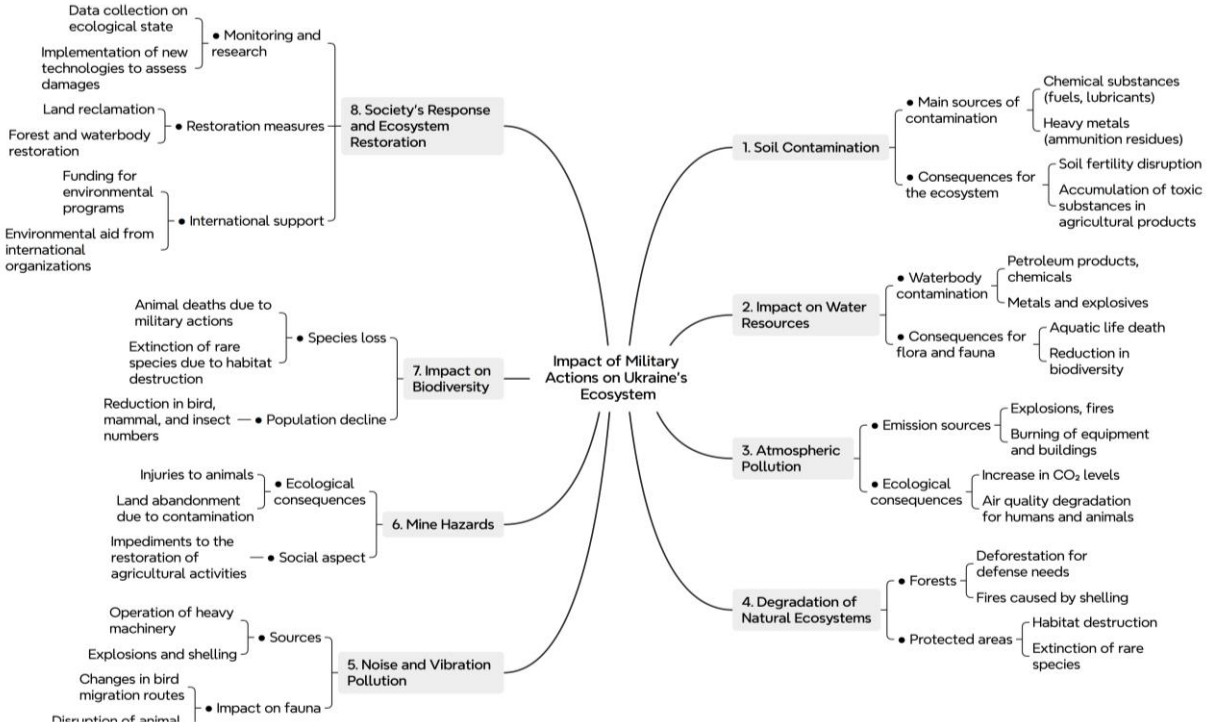

Fig. 1. Impact of hostilities on the ecosystem of Ukraine

2. Analysing satellite data and remote sensing

The analysis of satellite data and the use of remote sensing technologies is an important tool for monitoring environmental changes resulting from the hostilities and assessing the damage caused to Ukraine's natural resources.

Satellite technologies for monitoring environmental changes include:

– Observation of changes in the landscape. Satellite imagery allows us to assess the extent of damage to natural and artificial landscapes, including explosions, fires or massive forest burning.

– Assessment of soil and water pollution. Observation of water pollution through changes in water colour (e.g. due to the presence of oil products or chemicals) and water levels that the destruction of dams or water treatment plants may cause.

Remote sensing is a powerful tool for monitoring changes in vegetation and ecosystems, including in the context of military operations. High-resolution satellite technology can detect changes in green cover, including reducing or destroying forests, agricultural areas or natural areas. Such observations can provide a clear picture of the extent of environmental damage caused by military operations.

Remote sensing can also identify areas with the most significant environmental damage. Analysing changes in the reflection of light absorbed or reflected from the ground allows us to locate areas where hostilities have caused significant damage to the natural environment. This makes it possible to assess the extent and nature of the impact on biodiversity and identify priority areas for ecosystem restoration.

Monitoring atmospheric changes and air pollution is an important component of assessing the environmental impact of military operations. Satellite technologies provide data on the emissions of toxic gases and particles resulting from various destructive processes, such as fires, explosions and other hostilities. This makes it possible to identify areas with high levels of pollution, which can have serious consequences for human health and the environment.

In addition, satellite monitoring of Earth's surface temperature changes allows us to detect thermal anomalies that large fires or other artificial disasters may cause. Such anomalies indicate significant disturbances in atmospheric processes, which must be considered when assessing long-term environmental impacts.

Satellite data analysis is an important tool for studying the environmental impact of hostilities, and one of the main methods is the use of geographic information systems (GIS). These platforms allow for the integration of various data types, including satellite imagery in different spectrums and information on pollution and landscape changes. This makes it possible

to create detailed maps to assess the impact of hostilities on ecosystems, which is important for planning recovery efforts.

In addition, using satellite image processing algorithms allows for an in-depth analysis of changes that occurred in the areas before and after the hostilities. This makes it possible to accurately determine the extent of damage and assess the state of ecosystem restoration, which is important for the effective management of natural resources and the restoration of ecological balance.

Satellite monitoring is an essential tool for assessing the environmental impact of military operations. It allows observations of large areas without physical presence on site, which is especially important in dangerous environments. Satellite imagery provides a high scale of analysis, enabling coverage of even remote and hard-to-reach areas. In addition, this data can be obtained quickly, which is important for rapid response in times of war (Figure 2).

As Ukraine is currently experiencing a dangerous period and part of its territory is under occupation, we are unable to conduct field research. In such circumstances, satellite imagery becomes the only way to study environmental changes and assess the impact of military operations on the environment.

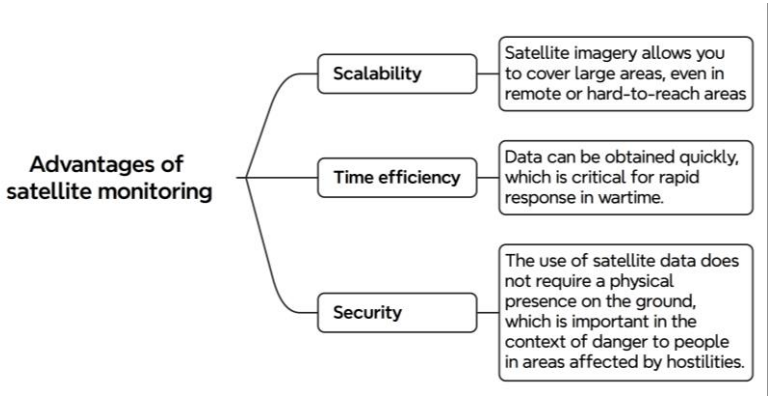

Fig. 2. Benefits of satellite monitoring in wartime

Analysis of satellite data and remote sensing is a powerful tool for monitoring and assessing the environmental impact of hostilities. It allows for the rapid detection and assessment of ecosystem changes, as well as effective decision-making on environmental restoration and protection.

3. The impact of military operations on the ecosystem of Dvorichansky National Park: analysis of changes in vegetation cover and prospects for ecological restoration

Earlier, we used satellite imagery to study the Zmiyvskyi and Kupianskyi districts of Kharkiv Oblast. Now, we will analyse the example of Dvorichansky National Park, allowing us to assess environmental changes in this important region.

The Dvorichansky National Nature Park, located in the Kharkiv region of Ukraine, is a unique natural area established in 2009 to protect steppe ecosystems and chalk deposits. The park covers an area of 3,131 hectares and features chalk slopes that have been formed over millions of years as remnants of the ancient seabed. These geological formations create unique conditions for the existence of rare species of plants and animals. The park's ecosystem is supported by the Oskil River, which provides water balance and helps to maintain the natural balance.

The flora of Dvorichanske includes many rare species, many of which are listed in the Red Book of Ukraine. The park is home to Red Book animals. In addition to its biological significance, the park is of great geological importance due to its Cretaceous deposits, which allow us to study the history of the region's geological development.

As of 2022-2024, the park is in the zone of active hostilities, which seriously threatens its ecosystem. The hostilities cause degradation of natural areas, pollution of soil and water bodies, and destruction of unique flora and fauna. This requires immediate attention from the scientific community to monitor the ecological state of the park and develop measures to restore it in the post-war period.

Since 24 February 2022, as a result of full-scale aggression, Russia has seized a significant part of the nature reserve fund of the Kharkiv region. Unique natural complexes, including the Slobozhansky National Nature Park and the Gomilshansky Forests, have been affected. The hostilities destroyed unique landscapes, species of flora and fauna, uncontrolled deforestation and mining of territories. Significant damage was also caused to nature reserves in Sumy and Donetsk regions.

Assessing the damage caused to protected areas remains difficult, but it is an important area for further scientific and practical research.

The authors have studied the impact of military operations on the ecosystem of the Dvorichansky National Nature Park in Kharkiv Oblast, in particular, in terms of changes in vegetation cover, pollution of natural resources and impact on biodiversity, and developed a strategy for the ecological restoration of this region.

The study analysed the dynamics of changes in the NDVI index for the period 2020-2024, which allowed us to assess changes in the state of vegetation due to military operations. The main factors of vegetation and soil degradation caused by hostilities were identified, and the extent of losses to the natural environment, including vegetation cover, due to hostilities was assessed. Based on the results obtained, recommendations for environmental rehabilitation and restoration of natural areas, including those affected by military conflicts, were developed.

The research methodology includes an integrative approach combining remote sensing, ecological analysis and geospatial modelling to study the park's condition comprehensively. The systems approach considers the interconnectedness of ecosystem components such as vegetation, soil, water and fauna. Comparative analysis allows us to assess the changes in the ecosystem before and after the outbreak of hostilities.

The **research methods** include geospatial analysis using Copernicus satellite images (Sentinel-2) to calculate NDVI and spatial modelling of vegetation changes using histograms and heat maps. Data analysis was carried out using Python to compare images, identify changes in NDVI and calculate average NDVI values. The ecological assessment includes identifying the most damaged areas and the potential for revegetation in less affected areas. For statistical analysis, time series of NDVI were used to determine seasonal and long-term trends.

The study used Copernicus data and Sentinel-2 satellite images to analyse changes in vegetation cover and calculate NDVI (Fig. 3).

NDVI (Normalized Difference Vegetation Index – Normalised Vegetation Difference Index) is an indicator that allows assessing the state of vegetation cover based on satellite data. The difference between the reflection of vegetation in the red and near-infrared spectrum calculates it. The study used Sentinel-2 satellite images from the Copernicus Data Space Ecosystem resource because of their high resolution and accuracy in detecting vegetation changes, which is especially important for analysing the impact of military operations on the ecosystem. The resource was used to build a time series and visualise the NDVI index, allowing us to assess vegetation cover changes based on satellite imagery.

Discussion of results. Figure 3 and the histograms (Figure 4) show the dynamics of changes in NDVI (Normalised Difference Vegetation Index) for the Dvorichanskyi National Nature Park in Kharkiv Oblast in 2020-2024.

Fig. 3. Satellite images of part of the Dvorichanskyi National Park for 10.09.2021 and 07.09.2024

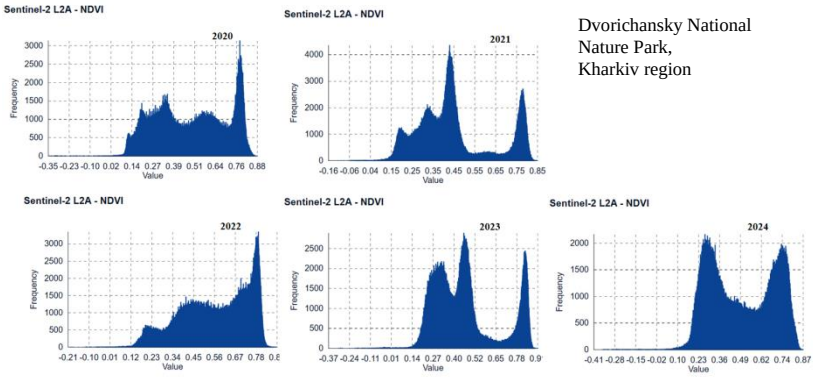

Fig. 4. Dynamics of NDVI changes in 2020–2024

In 2020–2021, before the outbreak of the war, there was a high peak of NDVI at values around 0.75–0.85, indicating the presence of dense and healthy vegetation. The distribution has precise two-hump shapes, which may indicate vegetation dominance with different density levels or ecosystem types in the park.

The years of the invasion 2022–2024 (after the outbreak of war) show a noticeable shift in the NDVI peaks towards lower values (0.1–0.5), indicating vegetation degradation. 2022 shows a broader range of values with a noticeable drop above 0.7. This is likely a consequence of hostilities such as bombing, artillery strikes and ground disturbance. In 2023 and 2024, there was a significant decrease in the proportion of high NDVI values, indicating a deteriorating ecosystem. The prolonged presence of hostilities may have affected vegetation regeneration.

The likely causes of the changes are related to direct and indirect impacts. Direct impacts include the destruction of vegetation due to fires, explosions and mechanical damage, and contamination of soil and water

bodies with explosives or heavy metals. Indirect impacts are caused by human intervention, noise, pollution and the inability to maintain the area due to mining or hostilities. The shift of the NDVI to lower values demonstrates the significant degradation of the park's ecosystem after the war began.

Figure 5 shows the dynamics of the average NDVI in 2020–2024. The red line marks the beginning of Russia's full-scale invasion.

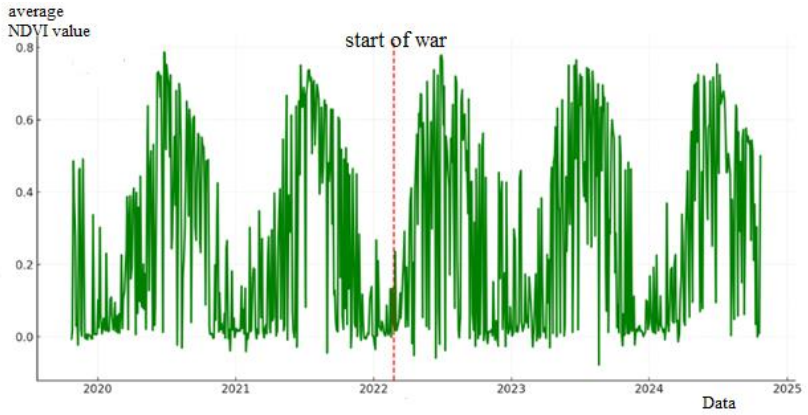

Fig. 5. Dynamics of the average NDVI for 2020–2024 (Sentine l–2)

Data analysis shows seasonal fluctuations. The NDVI shows cyclical dynamics characteristic of seasonal changes, with peaks in summer. After 2022, there is a decrease in the amplitude of NDVI values. This may indicate vegetation degradation due to hostilities, pollution, or changes in land use.

To analyse changes in vegetation cover based on NDVI histograms by year, the following steps were taken:

1. Data preparation. The NDVI data for four years (2021, 2022, 2023, 2024) were combined. NDVI ranges corresponding to different types of vegetation cover were determined.

2. Construction of NDVI histograms for each year to assess the distribution of NDVI values.

3. Calculate the area for each cover class (e.g. low, medium, high NDVI) in square kilometres based on the proportion of pixels.

4. Comparison of changes. The difference in area between years for each coverage class is determined.

We analysed seasonal fluctuations in the NDVI over the years (Fig. 6).

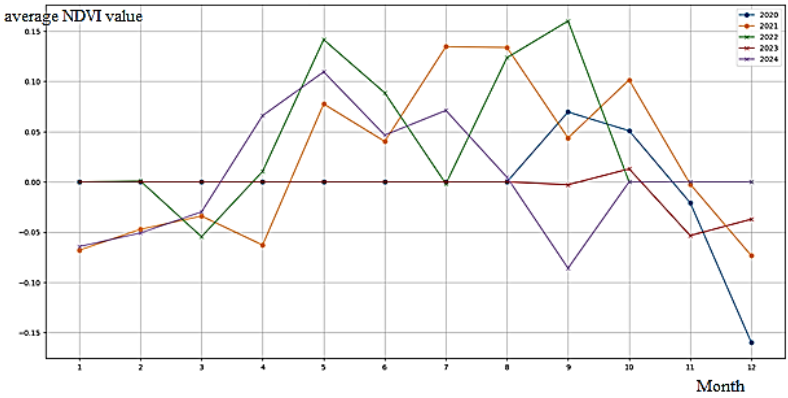

Fig. 6. Average NDVI value by month

Regarding the trend of seasonal fluctuations in NDVI, it can be seen that the graph shows that NDVI values fluctuate within each year, as is usually the case with vegetation depending on the time of year. Typically, we see higher values in the middle of summer (July-August) when the vegetation is most developed and lower values in winter when the plants are dormant. There are inevitable fluctuations in the NDVI each year, corresponding to different climatic conditions. This allows us to see how the vegetation changes from year to year.

In 2020 and 2021, we can see stable seasonal fluctuations with no sudden changes. The state of the vegetation looks stable, which leads to the conclusion that no significant external factors would substantially impact ecosystems (compared to 2022). The NDVI values in 2020 and 2021 show a clear seasonal trend: an increase from spring to summer (peak values in May -June) and a gradual decrease in autumn and winter. Average NDVI values before the war remained stable, with no significant fluctuations.

Figure 7 shows that 2022 is likely to differ from previous years due to the war in Ukraine. The NDVI values are lower or have more fluctuations after the outbreak of the war. This may indicate a significant impact on the state of vegetation, as the hostilities led to a decrease in vegetation or its deterioration due to damage to infrastructure, changes in land use, and lack of access to agronomic measures.

NDVI values for 2022 show significant fluctuations, especially in the spring and summer. This indicates the instability of ecosystems, which hostilities may cause. In the spring (March-April), the NDVI decreases compared to previous years, which may indicate a deterioration in vegetation conditions due to hostilities.

In 2023, NDVI values in the summer months (June – August) are significantly lower than in 2020-2021, indicating severe vegetation degradation. In 2024, the NDVI dynamics remain unstable, with substantial dips in spring and summer. This shows the ongoing destruction of ecosystems due to the hostilities.

If we compare the NDVI values after the outbreak of the war (especially for 2023 and 2024), we can see that there are additional changes in the state of the vegetation and even an increase in NDVI in active areas. This may also depend on the current situation in the country, the lack of agricultural work, and the level of restoration of the areas.

The graph clearly shows that the most significant vegetation change occurred after 2022, likely due to the outbreak of war. This decline can be interpreted as the war's consequences directly impacting ecosystems. The decline in NDVI in 2022 and further fluctuations in 2023 and 2024 confirm the profound impact on vegetation. The recovery in 2023 and 2024 shows that although vegetation is recovering somewhat, ecosystem changes can be long-lasting and significant.

Thus, the impact of hostilities is expressed as follows:

– Decrease in NDVI. Since 2022, NDVI values have decreased on average for all months, especially during active vegetation (spring and summer). This indicates a decline in vegetation, possibly due to physical destruction of areas, destruction of vegetation cover, or soil and water pollution.

– Seasonal instability. Since 2022, there have been significant fluctuations in the NDVI. For example, spring values are becoming less stable in different years, which may indicate a disruption of natural vegetation cycles due to military operations.

– Ecosystem degradation In 2023 and 2024, there is a significant decrease in NDVI in the summer months. This may result from long-term environmental damage, such as soil erosion, pollution, and changes in the water balance due to military activities.

We previously assumed that the damage was likely caused by fires, mechanical destruction from vehicle movements and shelling, chemical contamination from explosions and military materials, and loss of maintenance due to the cessation of human activity.

Before the war, the NDVI values were stable, with peaks in summer, while after the outbreak of the war, they decreased and became less predictable, especially in 2023-2024.

The war has caused significant environmental degradation in Dvorichany National Park, the impact of which may last for decades. It is important to continue regular monitoring of the vegetation using NDVI satellite data to

assess changes and plan restoration measures. Environmental rehabilitation will involve demining, cleaning contaminated areas, and planting trees and shrubs. In addition, engaging scientists to assess the long-term impact of hostilities on ecosystems and develop effective strategies for their restoration should be an important step in the post-conflict period.

To illustrate the results, we analysed the average NDVI values in the pre-war period (2020–2021) and during the period of hostilities (2022–2024), combining the relevant data (Fig. 7).

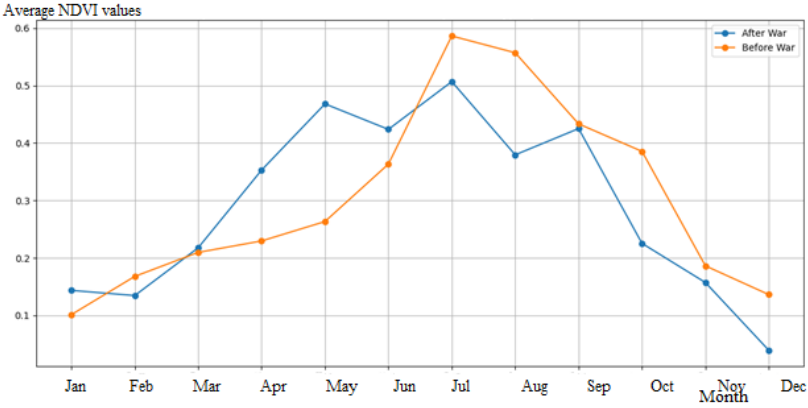

Fig. 7. Average NDVI values for the months before and after the outbreak of hostilities in Dvorichansky National Park in Kharkiv region

Figure 8 shows the average NDVI values for different months of the year before and after the outbreak of hostilities in Dvorichansky National Park in Kharkiv Oblast. Before the war, the seasonal peaks in NDVI occurred in June and July, when the vegetation in the region was at its most active, with a peak value of approximately 0.5. The NDVI values gradually increase from February to June and then decrease from August to December, corresponding to typical vegetation cycles in temperate climates. After the outbreak of the war, the maximum NDVI values in the summer months decreased, reaching around 0.45. There are noticeably lower NDVI values in spring (March-May) and autumn (October-November), which may indicate the impact of the hostilities on vegetation regeneration. In the winter months (December and January), the difference between pre– and post-war NDVI values is less significant, which may be due to the limited vegetation in this period.

Comparison of satellite images for different periods using the Python programming language made it possible to obtain a clear visualisation of the changes (Fig. 8). The main processing stages are implemented through an algorithm for comparing pixel value matrices and further visualisation of the results in the form of a heat map with a colour gradient from green (minimal changes) to red (maximum changes). The following methodology was used to analyse the satellite images:

1. Preliminary data processing:
– use of satellite images in GeoTIFF format for 2021 and 2024;
– normalisation of pixel values to the range of 0–255;
– geometric correction to ensure accurate image matching.

2. Analysis of changes:
– calculating the difference between the corresponding pixels of the images;
– creating a change mask using a threshold value;
– generating a heat map based on the intensity of changes.

3. Technical tools – Python programming language, libraries:
– NumPy for matrix operations;
– Matplotlib for visualisation;
– scikit-image for image processing;
– GDAL for working with geospatial data.

4. Statistical analysis:
– calculation of the area of changed territories;
– classification of changes by intensity;
– zoning of the territory by landscape type.

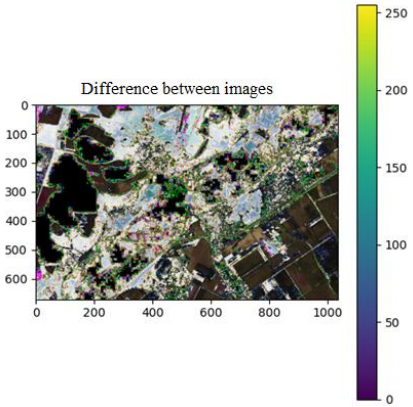

Fig. 8. Comparison of satellite images for 10.09.2021 and 07.09.2024

Thus, the heat map can be used to identify:

1. Areas of significant loss of vegetation cover. Light blue areas reflect a significant decrease in NDVI values, indicating severe vegetation degradation or its complete destruction. Possible causes:

– mechanical damage due to shelling, shell bursts, heavy machinery movement;

– chemical contamination from explosions, the use of toxic substances, or the effects of burning;

– fires that destroyed large areas of vegetation..

2. Areas of moderate change. Areas highlighted in green indicate minimal changes or stability in NDVI values. Possible reasons:

– areas are less intensively involved in military operations;

– natural vegetation is highly resistant to external influences.

3. Areas with no changes or localised improvement. Dark areas represent regions with no significant changes and a possible increase in NDVI. This may be caused by:

– the absence of human activity (e.g., cessation of agricultural activities);

– development of fast-growing plant species that have adapted to new conditions.

4. Spatial features of the impact. Hostilities have an uneven impact on the territory:

– in the areas with the greatest changes (light blue zones), strategically important objects or areas of intense fighting could be located;

– in the green and dark zones, the scale of destruction was smaller, allowing vegetation to survive or recover partially.

The image shows both a part of the Dvorichany National Park, a built-up area, and an agricultural area. The same algorithm for comparing pixel value matrices, which was made using Python, allowed us to identify separate zones and analyse the state of the park area (forests), the area of the settlement, and agricultural plots separately. The results of the analysis are shown in Table 1 and Fig. 9.

General information Damage distribution (Table 1)

The analysis shows that the highest percentage of damage was recorded in the settlement (60%), where 30% of the area was severely damaged. Forests and agricultural land suffered a lower level of damage – 45% and 35% respectively, with the majority of the area remaining unaffected in both categories (55% and 65%). Thus, settlements are the most vulnerable to the effects of hostilities.

Table 1

Degree of damage to the territories by category

Site	General information	Damage distribution
Forests	Total area 320 ha	Heavily damaged 48 ha (15%)
	Damaged area 144 ha	Moderately damaged 64 ha (20%)
	Percentage of damage 45%	Slightly damaged 32 ha (10%)
		No changes 176 ha (55%)
Agricultural land	Total area 480 ha	Heavily damaged 48 ha (10%)
	Damaged area 168 ha	Moderately damaged 72 ha (15%)
	Percentage of damage 35%	Slightly damaged 48 ha (10%)
		No changes 312 ha (65%)
Settlement	Total area 150 ha	Heavily damaged 45 ha (30%)
	Damaged area 90 ha	Moderately damaged 30 ha (20%)
	Percentage of damage 60%	Slightly damaged 15 ha (10%)
		No changes 60 ha (40%)
The entire area of the image	Total area 1080 ha	Reduction of vegetation 65%
	The average percentage of change 45%	Increase in vegetation 35%
	Maximum change of 65%	No changes 10%
	Minimum change 25%	

Figure 9 shows the ratio of damaged and unchanged areas by type of territory. The highest level of damage was recorded in populated areas (60%), while open areas were least affected (25%).

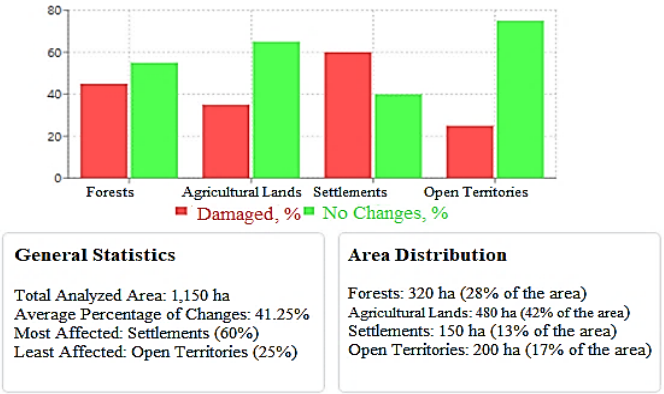

Fig. 9. Distribution of Changes by Types of Territories

Changes in the ecosystem caused by military operations can be related to the following factors:

1. Military operations have a significant impact on the ecosystem through a variety of factors that cause environmental degradation.
2. Mechanical destruction of landscapes through explosions, movement of equipment and trenching leads to loss of biodiversity, soil compaction and destruction of natural resources.
3. Fires destroy vegetation, cause soil degradation and reduce soil fertility.
4. Pollution of the environment by heavy metals and chemicals from munitions explosions causes long-term environmental problems.
5. Soil erosion due to the destruction of vegetation, especially in areas with steep terrain.
6. Disturbance of the hydrological balance and changes in the microclimate due to the destruction of water sources and vegetation, affecting ecosystem regeneration.
7. Restrictions on human activity due to hazards that impede ecosystem restoration (erosion control, vegetation restoration).
8. Loss of seasonal stability of NDVI reflects a decrease in soil moisture, destruction of water sources and microclimate disruption.

The main consequences are a decrease in biodiversity, environmental pollution, soil erosion and degradation of natural resources.

The effects of hostilities on the ecosystem are significant and complex. Vegetation degradation has a lasting impact on biodiversity, including reducing the number of animals that depend on these ecosystems (Table 2). Reduced vegetation cover also alters the local climate, reducing the area's ability to retain moisture and increasing the risk of soil erosion. After the end of hostilities, the affected areas will require significant rehabilitation efforts, such as demining, soil improvement and biodiversity restoration.

The recommendations include further monitoring of NDVI changes to assess the long-term impact of hostilities on vegetation. After the end of the war, it is important to engage ecologists to develop plans for restoring vegetation and ecosystems. Efforts should also be made to minimise further destruction of the natural environment during hostilities.

These measures will contribute to an effective assessment of the impact of the war and planning of recovery actions, and, if necessary, the analysis can be expanded for specific seasons or territories. Given the analysis of the environmental consequences of the hostilities in the Kharkiv region and the use of modern monitoring methods, including satellite data and remote sensing, further research should focus on the following aspects:

Table 2

Key findings on the ecological state of the Kharkiv region's ecosystems damaged by the hostilities

Category	Details
Soil and water pollution	Accumulation of toxic substances (heavy metals, oil products, explosives)
	Decrease in soil fertility
	Deterioration of water quality
Degradation of vegetation cover	Shelling, fires, destruction of natural areas
	Decrease in NDVI, indicating loss of biodiversity
Decrease in biodiversity	Animal deaths and habitat destruction
	Disruption of migration routes
	Reduction in the number of rare species
Destruction of protected areas	Significant damage to national parks and reserves
	Destruction of chalk ecosystems due to mechanical impact and fires
Mine threat	Land contamination by mines and unexploded ordnance
	Impossibility of safe use of territories
Social and environmental impacts	Destruction of infrastructure for environmental monitoring
	Negative impact on the quality of life of the population
	Long-term health risks

1. In-depth monitoring of ecosystems:

– Expanding the analysis of satellite data (Sentinel-2, Landsat) to assess changes in landscape, vegetation and water resources in other regions of Ukraine.

– Using the latest machine learning algorithms to automate the detection of ecosystem degradation.

2. Research on the effects of chemical pollution:

– Assessment of the long-term impact of heavy metals and explosives on soils, water resources and biodiversity.

– Development of environmental monitoring methods for areas with a high risk of pollution.

3. Analysis of ecosystem restoration:

– Study of natural processes of vegetation recovery in the affected areas.

– Development of strategies for targeted rehabilitation of damaged ecosystems, including national parks.

4. Socio-ecological approach:

– Study of the impact of environmental changes on local communities and their willingness to participate in the restoration of the natural environment.

– Analysis of opportunities to engage international organisations to support environmental initiatives.

5. Mine safety and its impact on ecosystems:

– Development of methods for monitoring and assessing the effects of mining on the environment.

– Study of the impact of demilitarisation of territories on biodiversity restoration.

Further research should take into account an interdisciplinary approach, integrating satellite data, field studies and socio-economic aspects. This will allow for a comprehensive understanding of the effects of the war and effective planning for the restoration of Ukraine's ecosystems.

4. Strategic measures for ecological restoration: the role of state policy and public initiatives

Proposals for state policy and civic initiatives in ecosystem restoration are aimed at a systematic approach to solving environmental problems caused by military actions (Figure 10). The state policy should include the development and implementation of a national programme that includes comprehensive measures for demining, clean-up of contaminated areas, re-vegetation and environmental monitoring. The legislative framework should be improved to ensure enhanced liability for environmental crimes and to introduce mechanisms for compensation for damages. Another important aspect is financing environmental initiatives through budgetary allocations, grants and international investments. Creating ecological reserves in the most affected areas is also advisable to preserve biodiversity and ensure sustainable use of natural resources. It is important to establish international cooperation to obtain technical, financial and expert support.

Public initiatives can include organising educational campaigns to raise public awareness of the importance of ecological restoration. Volunteer programmes can engage the public in concrete actions such as clean-ups and tree planting. Scientific research should also be supported by creating public funds to finance it, mainly to analyse the effects of war and develop recovery strategies. The development of eco-tourism can be a tool for raising financial resources, and establishing online platforms will facilitate practical cooperation between the state, the public and international organisations.

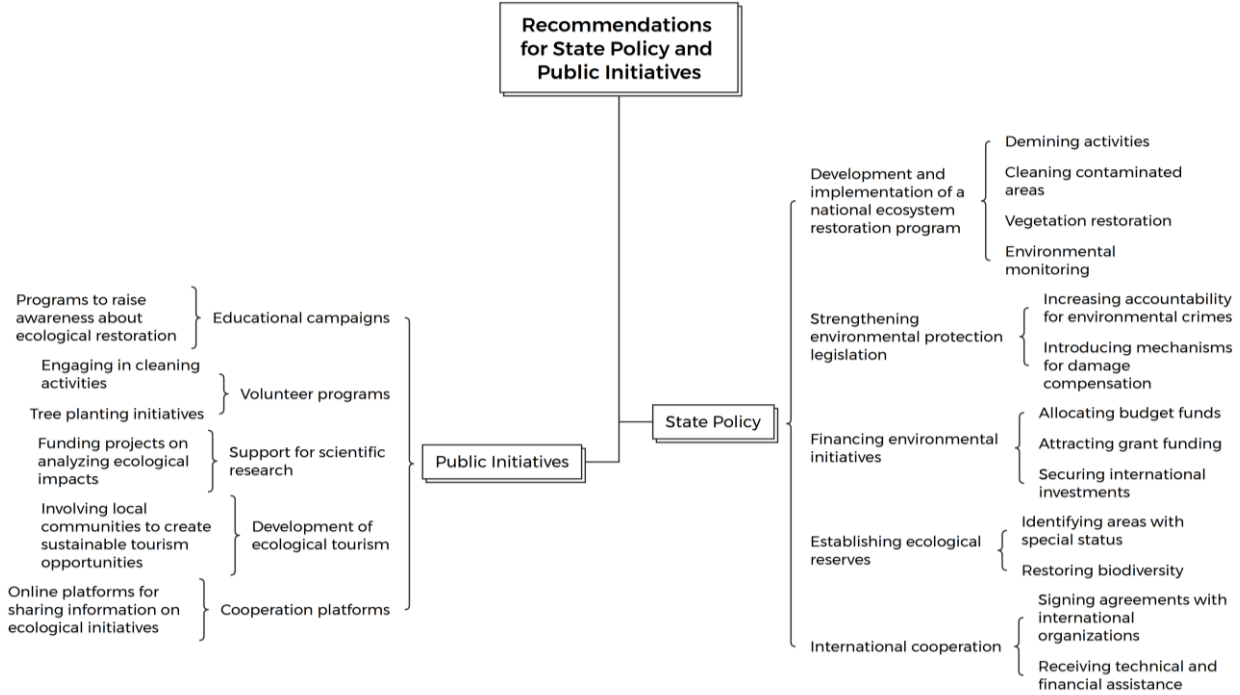

Fig. 10. Recommendations for state policy and public initiatives in the field of ecological restoration

These measures will ensure a comprehensive approach to ecosystem restoration, help improve the environmental condition of the regions and engage citizens in responsible management of natural resources.

CONCLUSIONS

Based on the results of the study, the following conclusions are formulated:

1. The large-scale impact of the war on the ecosystem of the Kharkiv region was manifested in significant destruction of natural areas, soil and water pollution, landscape degradation and loss of biodiversity. These long-term consequences require immediate measures to mitigate the damage and restore ecosystems.
2. Modern technologies have proven to be effective in monitoring environmental impacts, including satellite data analysis and the use of the NDVI index. These make it possible to detect changes in vegetation cover, assess the extent of losses and identify priority areas for restoration.
3. Restoration of ecosystems in the Kharkiv region requires a comprehensive approach integrating scientific research, public policy, and public initiatives. Cooperation between government agencies, scientists and international organisations is key to achieving sustainable results.
4. To minimise the environmental consequences of the war, it is important to develop and implement a national recovery programme, strengthen the legislative framework for environmental protection, create environmental reserves and provide financial support for recovery measures. Active public participation through volunteer programmes and awareness campaigns will contribute to effectively implementing these initiatives.
5. International cooperation is a prerequisite for successful environmental restoration, as the war in Ukraine has global environmental consequences. The exchange of experience and financial and technical assistance from other countries will contribute to faster environmental recovery and prevent similar disasters in the future.

The study lays the foundation for further research and developing a strategy for environmental recovery in Ukraine in the post-conflict period.

SUMMARY

The research explores the environmental impact of military actions in Ukraine, focusing on the Kharkiv region. It analyses soil, water, air, vegetation, and biodiversity degradation caused by warfare. Utilizing satellite monitoring and remote sensing, the study identifies key areas of ecological damage. Recommendations for ecosystem restoration include

creating a national rehabilitation program, strengthening environmental legislation, and fostering international collaboration.

The research underscores the importance of public and governmental initiatives in addressing ecological challenges, such as awareness campaigns, volunteer programs, and sustainable practices. Advanced monitoring technologies like NDVI are emphasized for assessing environmental changes and planning recovery efforts. This work lays the foundation for post-conflict ecological recovery strategies to ensure sustainable development in affected regions.

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