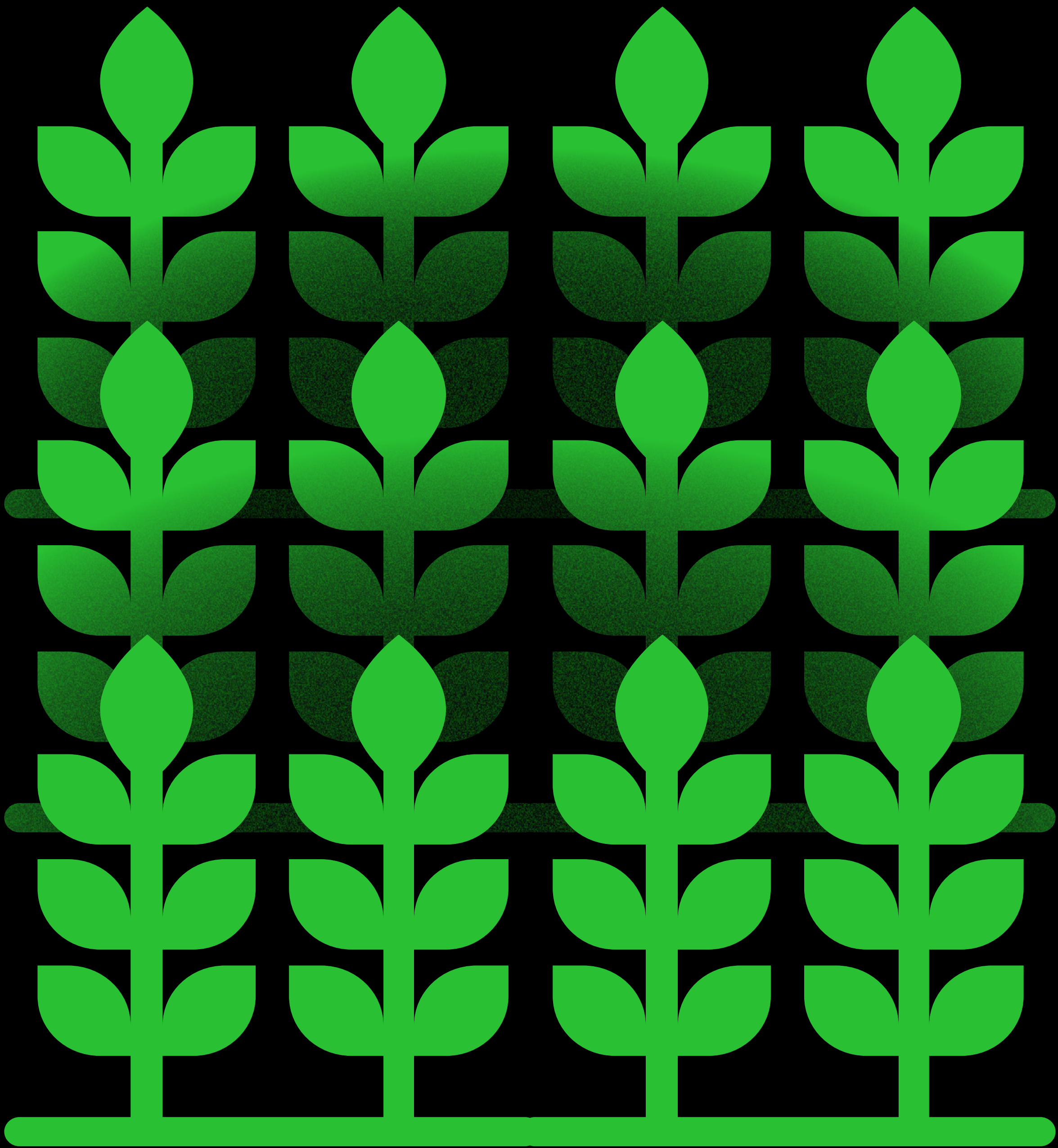

SUPPORT IN THE RESTORATION OF NATURE RESERVES IN UKRAINE: AN ACTION PLAN

UKRAINE NATURE

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“Support in the restoration of nature reserves in Ukraine: an action plan”.

Credits

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List of abbreviations

ACLED	–	armed conflict location and event data project
AOP	–	advanced oxidation process
CMC	–	confirmed mine-contaminated
FIRMS	–	fire Information for resource management system
GBIF	–	Global Biodiversity Information Facility
GIS	–	geographic information system
MAI	–	metal accumulation index
MAI	–	metal accumulation index
MPC	–	maximum permissible concentrations of pollutants
NNP	–	national nature park
PMC	–	potentially mine-contaminated
REBR	–	radiation and ecological biosphere reserve
UXO	–	unexploded ordnance
VIIRS	–	visible infrared imaging radiometer suite
NDVI	–	normalized Difference Vegetation Index
NIR	–	near-infrared band images
R	–	red band images

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Executive Summary

This white paper is a report on the results of ecological study on the consequences of the Russian war in Ukraine in four protected nature reserves that are part of the Emerald Network – the Chornobylskyi Radiation and Ecological Biosphere Reserve (REBR); the Desniansko-Starohutskyi National Nature Park (NNP); the Holosiivskyi National Nature Park (NNP), and the Hetmanskyi National Nature Park (NNP). Ukraine-Nature project delves into the significant yet often neglected environmental repercussions of the Russian invasion of Ukraine, highlighting the adverse effects on the soil, biodiversity, and forests. The authors found that nature in these reserves are endangered by landmines, wildfires caused by artillery shelling and purposeful setting of fires in forested areas, armed clashes between opposing armed forces, military occupation of the land, and the movement and maintenance of military vehicles and machinery. This has resulted in widespread destruction and contamination of natural habitats and has disrupted wildlife populations and ecosystems. Damages to forested areas in each reserve are extensive and soil sampling in the combat damaged zones conducted in October 2022 indicates that the impact of military activities on soils in the studied areas is particularly significant, requiring special management and monitoring when peace returns to these reserves.

In this context, this white paper aims to provide an overview of the impacts of the war on the environment in four Ukrainian protected areas, namely the Chornobylskyi REBR, Holosiivskyi NNP, the Desniansko-Starohutskyi NNP, and the Hetmanskyi NNP. To address these aspects, the Ukraine-Nature team relied on several methods including bibliometric analysis, key informant interviews, and GIS analyses based on satellite pictures as well as secondary data gathered by experts from the Ukraine Nature Project in two stages: during the expedition and extracted from databases (ACLED, FIRMS, Ministry of Defence of Ukraine, and State Emergency Service of Ukraine) and processed using QGIS software. Current evidence suggests ecological recovery of these nature reserves will be challenging, and some post-conflict restoration work may not be possible. In some cases, it is increasingly likely that some indigenous wildlife species and portions of the landscape will not recover and are likely to be gradually lost completely over time.

The white paper further explores various methods as well as sustainable-oriented solutions aimed at mitigating these effects on the environment. Furthermore, it discusses the immediate and long-term challenges Ukraine faces in it's recovery efforts, emphasizing the need for environmentally conscious approaches to address these issues. One of the main recommendations, for example, would be to ensure legal accountability for environmental war crimes and to intensify the efforts to stop the war. The limited access to the territories due to mining and shelling restricts researchers and society in acting towards recovery, and the main activities would include constant monitoring and assessment of environmental damages caused by the war.

Ukraine-Nature results should inform future management decisions, legislative initiatives, and international awareness regarding the environmental consequences of war.

1. Introduction

Russian invasion of Ukraine poses great challenges for global society, especially with the present environmental circumstances and the need to meet climate change goals [30]. The environmental impacts include the release of toxic materials into the air, water, and soil from explosions, combustion, fires, military waste, and heavy military machinery. The relentless nature of modern warfare poses substantial risks to the nature.

The environment is typically under-prioritised during conflicts, particularly in the face of so much human suffering. However, both human rights and ecosystems depend on a healthy environment. Moreover, having access to clean water, air, soil, and biodiversity, as well as access to ecosystem services, would be one of the most important conditions for displaced people to come back to Ukraine [44, 45].

The natural landscape of Ukraine, particularly of the protected nature reserves belonging to the Emerald Network, is changing as a result of the Russian war in Ukraine. Data on the transformation of the landscape and, in some locations, complete degradation of unique areas is lacking. This lack of comprehensive research documenting the ecological changes caused by military activities taking place in protected nature reserves is a significant data gap and could affect the success of post-conflict restoration work in the future as well as actual conservation activities.

Ukraine joined the Bern Convention on the Conservation of European Wildlife and Natural Habitats in 1996 [56]. The country initiated the implementation of relevant policies, environmental-protection legislation, and the creation of Emerald Network nature reserves in 2000 with the adoption of the national state program "National Program for the Formation of the National Ecological Network of Ukraine for 2000–2015." Ukraine's commitments to the Emerald Network were originally slated to be fully implemented by 2020, as outlined in the 2015 revised calendar for Emerald Network Implementation.

The launch of the Russian Federation's military offensive in February 2022 has greatly affected Ukraine's sovereign territory in at least eight regions, including the eastern region of Donetsk and Luhansk, which were already affected by the armed conflict beginning in 2014. The war in these and other sites has greatly affected the progress of Ukraine's Emerald Network implementation because many of Ukraine's designated Emerald Network reserves have been, or currently are, occupied by the Russian Federation military or Ukraine defence forces.

Among the many harmful consequences to nature conservation efforts stemming from the war are the physical damage to protected areas and the absence of management, research, and actions needed to protect and preserve endangered plants and wildlife. Management problems emerged due to the lack of financial incomes and military obligation of employees. Russia's war against Ukraine has already affected 20% of protected areas, where Russian army occupied eight nature reserves and ten national parks, posing risk to important wildlife sites threatened with destruction, including 2.9 million ha of the Emerald [15, 44, 45, 66]. These territories are a significant part of the nature protection network of Europe, which is protected within the framework of the EU and Council of Europe legislation. 16 Ramsar sites with an area of more than 600,000 ha are under threat of destruction [57].

On 21 September 2022, Ukraine's Supreme Council adopted Bill 7475 in its first reading. The bill is intended to strengthen protection of Ukraine's state borders, but content-wise, it is primarily devoted to procedures for removing land from the Nature Reserve Fund (NRF) [36].

Infrastructure support for the border zone requires significant intervention in ecosystems: building defence structures, infrastructure, and roads, draining swamps, and expanding clearcutting in forests. Thus, any hardening of the border undoubtedly affects natural ecosystems [15, 66].

The environmental devastation wrought by the war extends beyond the immediate degradation of soil, forests, and biodiversity; it poses a cascading threat that exacerbates the humanitarian crisis by directly and indirectly affecting the health and well-being of the affected populations [5, 26, 45, 50, 44]. The war's impact on biodiversity is particularly alarming, with habitat destruction posing a direct threat to the survival of numerous species. Forests, wetlands, and other natural habitats face severe damage, leading to a significant loss in biodiversity. Furthermore, the chaos and noise associated with warfare disrupt wildlife migration patterns and breeding cycles, exacerbating ecological imbalances [17, 61].

The current state of landscape complexes within protected areas, now altered due to hostilities, demands heightened attention and organizational measures. The absence of extensive research on the territories of protected areas impacted by military activities often leads to the transformation or even complete degradation of these unique landscapes. In some cases, restoration of these areas only through post-military intervention may create an insurmountable challenge of the gradual loss of individual biotic species and entire landscape complexes.

Moreover, there's an imperative need to analyse the spatial distribution and intensity of hostilities within the territories of existing protected areas. This analysis should aim to identify zones with varying levels of resilience to military and technological stress, ensuring a focused approach to preservation and restoration efforts. As far as wartime environmental degradation takes place across thousands of incidents across hundreds of square kilometres, the methods of environmental impacts study have to be carefully selected [50].

In response to this crisis, the Ukraine-Nature team has concentrated its research efforts on four areas within the Kyiv and Sumy regions (Figure 1): the Chornobylskyi REBR, the Holosiivskyi NNP, the Desniansko-Starohutskyi NNP, and the Hetmanskyi NNP. These areas were selected based on the data from official sources indicating that they have all suffered from military actions, are part of the Emerald Network, and were not under occupation as of May 2022. This focused approach underscores the critical need for targeted research and restoration efforts to mitigate the war's environmental impact.

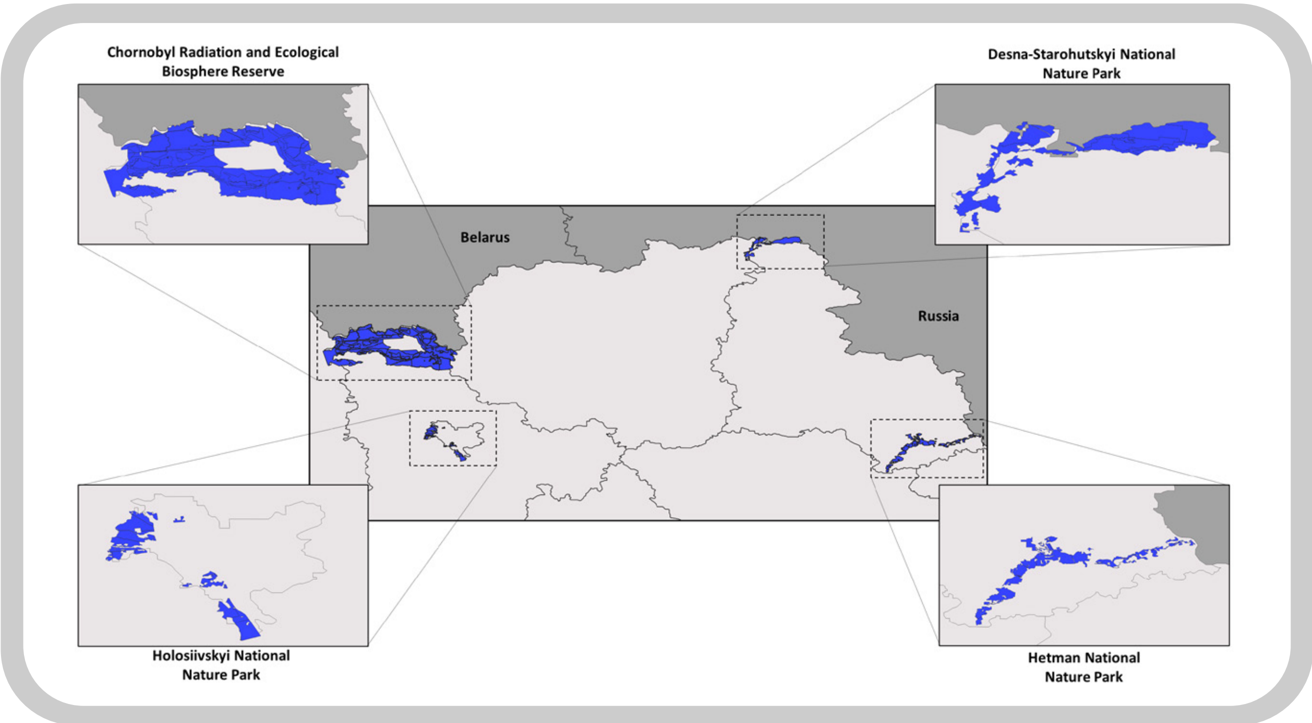

Figure 1. Selected Ukrainian protected areas?

2. Assessment Methods

This white paper aims to foster a great understanding of the impacts of the war on the environment with a focus on Ukrainian preservation areas. To obtain the results, the authors relied on several methods including bibliometric analysis, key informant interviews, soil samples tests and GIS analyses based on satellite pictures as well as secondary data gathered by experts from the Ukraine Nature Project in two stages: during the expedition [53] and extracted from databases (ACLED, FIRMS, Ministry of Defence of Ukraine, and State Emergency Service of Ukraine) [4, 16, 33, 54, 54].

2a. Bibliometric Analysis

The Team of the Ukraine-Nature project adopted a bibliometric analysis to understand the landscape of what the military drivers are and how they impact several dimensions of the environment. At the same time, it helped to study practices helping to resolve impacts caused by the military action. In order to perform data analysis, the authors adopted the VOSviewer software [62], where selected peer-reviewed documents were used to perform the bibliometric co-occurrence of terms. The terms that appear close to each other are expected to be associated, generating a thematic cluster due to their co-occurrence frequency [46, 58, 62, 62].
The summary of the selected results is presented in Tables 5, 6, and 7 "Examples of measures to address the impacts of military actions on the soil, forests, and biodiversity".

2b. Studied Areas Affected by Military Actions

Based on the information on war incidents from ACLED (Armed Conflict Location & Event Data Project) [4], and given the moderate spatial accuracy of the incidents' geographical locations, the density of the incidents was calculated. A neighbourhood of a 3 km radius was selected for density calculation with a raster output of 250 m spatial resolution. The risk of mine and/or UXO (Unexploded Ordnance) contamination in the studied protected nature reserves was assessed using the official geo-portal of the State Emergency Service of Ukraine [54] as of 1 November 2022. There are two categories of land in terms of mine contamination distinguished on the official geo-portal: potentially mine contaminated (PMC) and confirmed mine-contaminated (CMC) territories.
The number of fires recorded within the four studied protected nature reserves was assessed based on the data extracted from the Fire Information for Resource Management System (FIRMS). Information from the Visible Infrared Imaging Radiometer Suite (VIIRS) was employed with a spatial resolution of 375 m, which allows detection of smaller fire events unlike other similar instruments for fire monitoring. Each record in the accessed database represents the centre of respective pixels, thus enabling detection of fires not smaller than 14 ha. Therefore, each individual pixel is considered as a separate fire event, disregarding information in the neighbouring pixels and time sequence.
All the described military actions caused by the Russian Federation's military offensive (occupation, mine danger, fires caused by shelling, ground battles (armed clashes), and remote violence (explosions, shelling)) could lead to anthropogenic changes to soil properties based on 160 previous study results covering disturbances during military training and warfare analysed by Broomandi et al. (2020) [8]. Information extracted from databases and satellite images became a basis and was proceeded by field expeditions and soil sample analyses for a comprehensive study documenting physical/chemical disturbances in soils following military activities in studied areas.

2c. Estimation of Damages to Forested Areas due to the Fires

To identify the extent of burnt area within the four study areas, the following steps have been made. First, the reflectance images with cloud-free observations captured by a constellation of Sentinel-2 satellites were selected individually for each area. One of them was from 2021 (before the full-scale war started), while others were acquired in 2022. Then, we classified each set of images using four spectral bands (red, green, blue, and infrared) complemented by an NDVI band computed for the same dates as

the analysed images. The classification employed a Random Forest algorithm [22] for which training polygons were manually delineated based on the freely available high-resolution imagery from Google Earth or the same images that undergo classification. Since the acquisition dates of processed images for the study area were different, the classification procedure was run separately for the study area.
The results were complemented by an analysis of the Planet's satellite images (https://www.planet.com/). For the Chornobylskyi REBR, satellite images from March and May 2022 were used, while for the whole Desniansko-Starohutskyi NNP, we relied on the images of up to 0.5 m resolution acquired on 15 and 27 May 2023 from Planet. For the assessment of tree losses, the NDVI was calculated using satellite imagery provided by Planet Labs for both near-infrared (NIR) and red (R) band images. Threshold values were applied to the NDVI images to classify different land cover types. There are often seasonal fluctuations in the vegetation index, as well as fluctuations caused by the state of the atmosphere at the time of the shooting. Therefore, often, in addition to the change in the index, it is also necessary to know its threshold value, which indicates the loss of tree cover. Information extracted from databases and satellite images was processed by QGIS software (http://qgis.org). Figure 2 shows the spatial dimension of the impacts on the environment in the four protected areas. The blue polygons represent areas that experienced occupation by the Russian military forces in February-April 2022; the red polygons unveil the burnt areas due to explosions and battles in these regions. The dotted polygons, in turn, indicate areas that potentially contain land mines, and the red dots show the explosions as well as remote violence and battles. A detailed description is presented in the Results section.

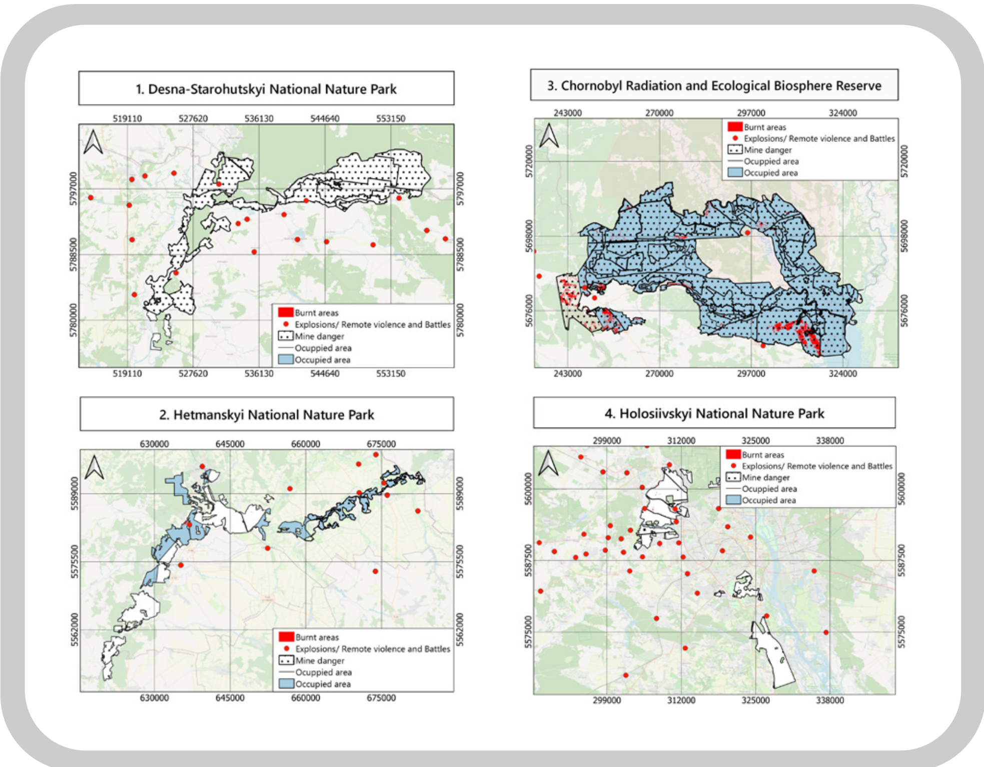

Figure 2. Distribution of military actions recorded in the studied areas

Based on the data from ground observations and information extracted from databases and satellite images, the following threshold value was determined for fires on the territories of the Chornobylskyi REBR and Desniansko-Starohutskyi NNP. The forest management map, combined with the produced map of losses, enabled us to estimate the volume of tree cover losses by area and stock and classify it using the rating evaluation method by the degree of impacts on forests: None, Low, Medium, Above Medium, High, or Extremely High.

Maps of the territories of the Desniansko-Starohutskyi NNP and Chornobylskyi REBR were divided using a regular grid of 1*1 square kilometres, each cell containing a unique identifier (Figures 3 and 4). The assessment method of rating evaluation with the same grids and unique identifier was also used for the soil and biodiversity impacts assessment but using different criteria, which is described in the 2e subsection.

2d. Estimation of Damages to Soils

Soil sampling was conducted in October 2022 by Dr. Anastasia Splodytel. Together with the preservation areas' representatives and the security service, she travelled to the parks to collect soil and water samples and examine the territories in order to evaluate environmental damages, particularly to the soil. During these expeditions to the four protected nature reserves, 63 samples were collected from the combat damage zones and 20 background samples from the study areas.

The sampling locations were chosen to represent different levels of suspected potential contamination with heavy metals and explosive remnants. Several soil samples were collected from the berm and crater bottoms directly in the area of hostilities, while other samples were collected from the area between the line of fire and the targets. Additional samples were collected outside the area of military influence to provide background concentrations of heavy metals in natural soils. All samples were collected from 0–5 and 5–15 cm depths. The purpose of sampling at the depth of 5–15 cm was to assess potential leaching of heavy metals into deeper soil horizons.

The main objective of the initial sampling phase was to identify the composition and levels of heavy metals and explosive residues in the study areas. The history of the areas use prior to the outbreak of hostilities and an examination of the weapons used were considered when identifying potential contaminants.

The second stage of soil analyses was the preparation of samples in the laboratory for chemical analysis: 1) Drying at 37°C; 2) Separation of soil and organic fraction; 3) Grinding; 4) Digestion; 5) Dilution; 6) Centrifugation; 7) Analysis.

At the third stage, the heavy metal content was measured. The content of heavy metals was determined using the ICP-OES method (Inductively Coupled Plasma – Optical Emission Spectrometry) at the Lodz University of Technology. To assess the level of pollutants in the soils of the protected areas, the values of maximum permissible concentrations of pollutants (MPC) were used. The obtained content of gross forms was compared not only with the MPCs but also with the background content of the natural soil.

The soil sample analyses found that the protected areas are contaminated with elements of hazard classes I-III, such as lead, manganese, zinc, copper, vanadium, strontium, etc. The area contamination exceeds the regional background values but is mostly within the MPCs. This is due to the specifics of military impacts caused by the use and operation of weapons systems and military equipment.

The degree of potential soil contamination of the national parks was assessed by the density of mining and fire intensity and processed by QGIS software (http://qgis.org). The initial geospatial data are datasets on the mining of national parks and recorded burned areas. For each protected areas, a regular grid of 1*1 square kilometres, each cell containing a unique identifier, was created as described earlier.

2e. Estimation of Damages to Biodiversity

There were encountered several challenges during the development and standardization of the methodology for assessing biodiversity loss in the protected areas affected by the armed conflict. Specifically, there was a lack of equivalent assessment or species diversity monitoring for the four studied protected areas at the same level. Some of these areas did not conduct quantitative assessments of rare biotic components with geospatial references and did not carry out comprehensive inventory accounting of natural habitats. Therefore, the analysis of biodiversity loss due to war-induced fires was based on a combination of biodiversity and environmental monitoring data from the scientific departments of the studied nature reserves, forest management maps, data from open biodiversity databases (GBIF; INaturalist) [18, 24], and the degree of soil disturbance.

An assessment was done in the form of a numerical rating, also known as „rating evaluation". The utilization of numerical rating facilitates a structured approach to comparing and analysing diverse entities or phenomena. Through this method, each object or phenomenon is assigned a numerical value, typically within a predefined scale, reflecting its attributes, quality, or performance relative to others. By organizing these numerical ratings in a comparative ranking, it becomes easier to discern patterns, trends, or differences among the objects assessed. Moreover, this approach enhances visualization by providing a clear representation of the relative positions of different objects based on their rating indicators. Visual aids such as GIS tools can be employed to present this information effectively, aiding in decision-making processes, identifying areas for improvement, or highlighting strengths and weaknesses within a set of objects. Overall, the use of numerical ratings in assessment facilitates a systematic and objective means of evaluating and comparing entities, contributing to informed decision-making and enhancing understanding of complex datasets or scenarios.

The rating assessment was based on the presence or absence of species listed in the Red Book of Ukraine and Resolution 6 of the Bern Convention, as well as the presence or absence of natural habitats listed in Resolution 4 of the Bern Convention. According to this scale:

- 0 points (None) were assigned to standard square plots if the Red Book of Ukraine species and Bern Convention species or habitats were not recorded within their territory;
- 1 point (Low) was assigned to standard square plots if potential habitats listed in Resolution 4 of the Bern Convention could potentially be found within their territory;
- 2 points (Medium) were assigned to standard square plots if potential Red Book of Ukraine or Resolution 6 of the Bern Convention species and habitats listed in Resolution 4 of the Bern Convention could potentially be found within their territory;
- 3 points (Above Medium) were assigned to standard square plots if the Red Book of Ukraine species were identified within their territory;
- 4 points (High) were assigned to standard square plots if habitats listed in Resolution 4 of the Bern Convention were identified within their territory;
- 5 points (Extremely High) were assigned to standard square plots if both the Red Book of Ukraine species and habitats listed in Resolution 4 of the Bern Convention were identified within their territory.

Areas with potentially existing rare species and natural habitats were identified according to the forest management data, where, for example, oak forests older than 100 years were classified as natural habitats G1.8 – Acidophilous Quercus woodland. In addition, potential presence of the Red Book of Ukraine and the Berne Convention (Resolution 6) rare species was determined based on verbal reports of protected nature reserves staff.

Based on the biodiversity data and the degree of soil disturbance rating assessment, a combinative matrix of the military action's impact on biodiversity was formed (Table 1).

BIODIVERSITY/HABITAT

SOIL DISTURBANCE

	None	Low	Medium	Above Medium	High	Extremly High
None	0	0	1	1	2	3
Low	0	1	1	2	3	3
Medium	1	1	2	2	3	4
Above Medium	1	1	2	3	4	4
High	1	2	3	4	4	5
Extremely High	2	3	4	4	5	5

Table 1. Biodiversity assessment matrix

Methods:

1. Literature review (VOSviewer)
2. Secondary data analysis: data bases (ACLED, FIRMS, Ministry of Defence of Ukraine and State Emergency Service of Ukraine)
3. Remote sensing
4. Mapping
5. Soil and water samples collection and analyses
6. Key informant interviews
7. Field observations
8. Data analysis (rating assessment, statistical)

3a. Chornobylskyi Radiation and Ecological Biosphere Reserve

The Chornobylskyi REBR was officially established on 26 April 2016, exactly 30 years after the Chornobyl tragedy, by President's Decree with the aim of preserving the most typical natural complexes of Polissia in their natural state, ensuring support and increasing the barrier function of the exclusion zone and the zone of unconditional (mandatory) resettlement, stabilizing the hydrological regime and rehabilitating territories contaminated with radionuclides, and promoting the organisation and conducting of international scientific research. The Reserve is unique and the largest in Ukraine, covering almost 227 thousand ha, or 2/3 of the exclusion zone territory [9]. There is a large deal of diversity, including 23 terrestrial, 7 aquatic phytosystems, 5 distinct landscapes, 120 species of lichens, 200 species of mosses, 303 species of vertebrates, and 1256 species of higher plants.

The territory of the Chornobylskyi REBR borders Belarus. It was through local roads that Russian troops entered Ukraine in the first days of the full-scale invasion. At the end of February 2022, in anticipation of an invasion, the Reserve administration pre-evacuated workers, leaving people only in critical positions. Most of the staff, including the scientific department, saw the consequences of hostilities already in April, after the liberation of their territory.

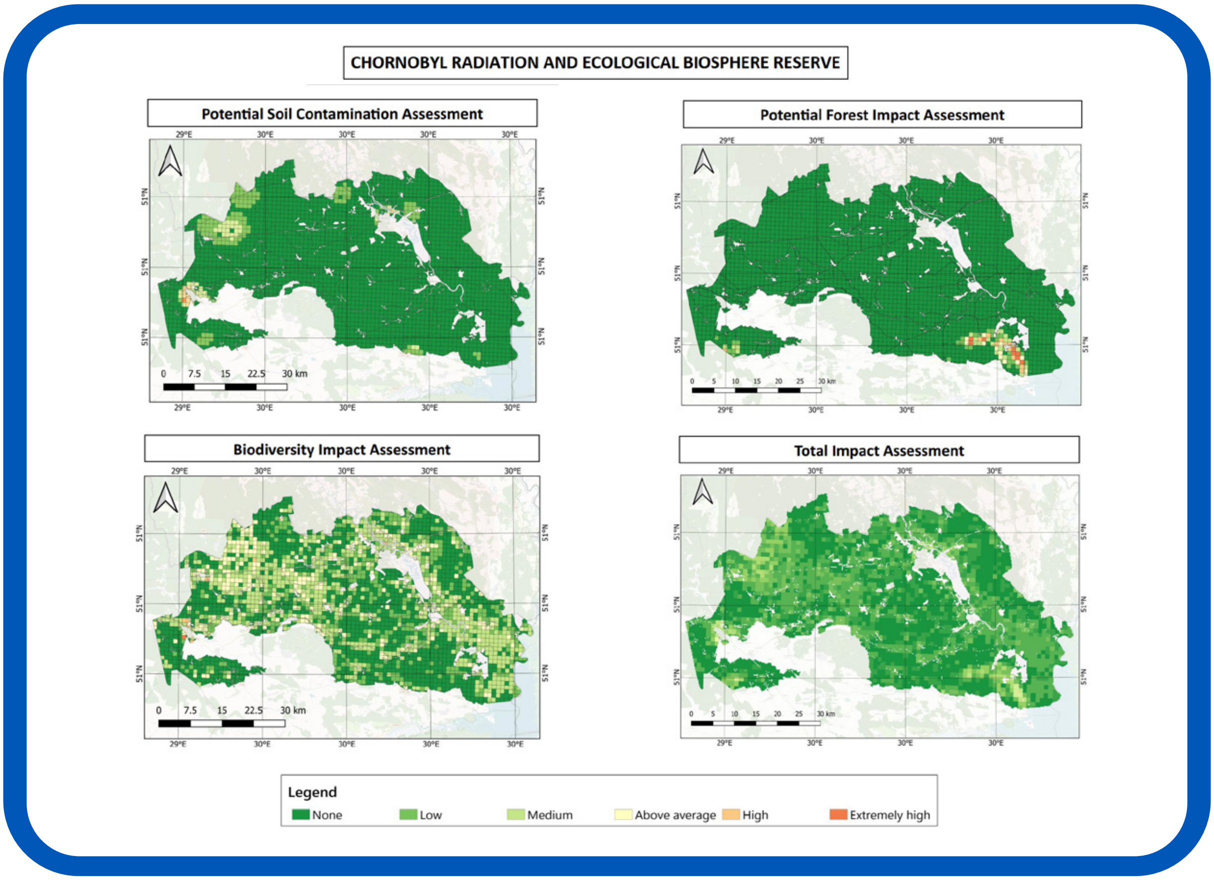

Figure 3. Chornobylskyi Radiation and Ecological Biosphere Reserve

MILITARY ACTIONS

The Chornobylskyi REBR experienced direct occupation of about 94% or 213,000 ha by Russian Armed Forces and was out of the area under governmental control between 24 February and early April 2022 (about 1,5 months in total). Project data show that almost the entire territory of the Chornobylskyi REBR is classified as PMC, except only 12 ha marked as CMC (confirmed mine-contaminated). Control over these territories has been lost due to contamination by unexploded ordnance and mines, as well as increased security measures along the state border caused by the risk of repeated incursions. Computer equipment and research equipment were stolen, as well as cars. Additional research and equipment (camera traps) are needed to study the loss of fauna.

IMPACTS ON SOIL

Due to the military impact, mechanical and chemical pollution of the soils of the Chornobylskyi REBR were observed (Figure 3). Chemical pollution was mainly caused by fires resulting from the use of weapons systems. According to the Chornobylskyi REBR data, during the occupation of the Chornobyl NNP Exclusion Zone (in the period from 24 February 2022 to 1 May 2022), fires caused by the occupiers damaged soil cover on the area of 31,760 ha (14% of the territory).
As a result of pyrogenic impact, the physical and chemical properties of the soil cover have changed. A change in acid-alkaline conditions towards a neutral pH reaction was quite expected for the soils of the areas affected by fires. On the burned areas, humus substances disappeared and a hydrophobic layer, which limits water infiltration, was formed. Reduction in the content of water-soluble compounds and neutralisation of the pH contributed to the

Soil	Ni	Co	V	Cr	Cu	Pb	Zn
Conflagration	75,0	1,7	28,0	17,0	32,0	45,0	52,0
Background	15,0	0,8	12,0	8,0	10,0	12,0	20,0
MPC	20	-	-	100	33	32	55

Table 2. Gross content of heavy metals in the background and pyrogenically degraded soils of the Chornobylskyi Radiation and Ecological Biosphere Reserve (mg/kg)

mineralisation of organic matter and differentiation of the soil profile under the conditions of increased exposure to metals, e.g. an increase in the calcium content by 4,3 times and a decrease in magnesium by 2 times were detected.

Heavy metal pollution is a consequence of artillery shelling and other military activity. Our results showed that concentrations of gross forms of all studied elements in soil samples from the burning area (as a result of a fire provoked by shelling) have many times higher values compared to the background soil. In particular, an increase in potassium by 3,5 times, magnesium by 1,3 times, nickel by 3 times, and vanadium by 4 times was recorded (Table 2). In contrast to the background samples, the presence of lead and zinc was detected in the range of 8–12 mg/kg.

According to the additional results of the ICP analysis with inductively coupled plasma, in soil samples from a burned area (Kupovate village), the concentrations of gross forms of all studied anthropogenic metals were several times higher compared to the background soil.

In addition to chemical pollution, soils of the Chornobylskyi REBR suffered from mechanical pollution. In the burned areas, removal of humic substances and formation of a hydrophobic layer, which limits the infiltration of water, are observed. Mechanical disturbance of the soil cover (tunnels, dugouts, etc.) accounted for about 6% of the Reserve's territory and did not pose significant threats to the territory's landscapes.

IMPACTS ON FORESTS

In 2022, in the Chornobylskyi REBR, biodiversity was damaged in an area of 31,760 ha out of 227 thousand ha as a result of fires (Table 3). In particular, pine coniferous plantations suffered extensive damage. Notably, large annual fires are typical of these areas and occurred even without the impact of military operations. During the Russian occupation, the REBR faced massive fires of high fire hazard class vegetation, such as young pine forests, fallows, meadow waste grounds, and wetlands with dry reeds and wetland grasses.

IMPACTS ON BIODIVERSITY

Estimated impacts on natural habitats and rare biota ranged here from None to High. The following types of natural habitats of Resolution 4 of the Berne Convention were marked for areas with a level of damage to biodiversity from above medium to extremely high moderately negative and negative impact: C - Inland surface waters: C1.2 - Permanent mesotrophic lakes, ponds and pools; D - Mires, bogs and fens: D5.2 - Beds of large sedges normally without free-standing water; E - Grasslands and lands dominated by forbs, mosses or lichens: E1.9 - Open non-Mediterranean dry acid and neutral grassland, including inland dune grassland, E3.4 - Moist or wet eutrophic and mesotrophic grassland; G - Woodland, forest and other wooded land: G1.5 - Broadleaved swamp woodland on acid peat, G1.8 - Acidophilous Quercus-dominated woodland.

All these biotopes have been affected to varying degrees by military operations. In these territories, a moderately negative, negative, and highly negative impact on habitats, places of migration, reproduction, and feeding of a number of species that are included in national and international nature lists was indicated, among which birds, reptiles, bats, and other mammals. It is interesting to note that no rare representatives of the flora were recorded in the affected area, but this does not rule out the high probability of their presence within the identified natural habitats of Resolution 4 of the Berne Convention. There have been detonations of animals caused by explosive objects. Due to the limited access, it is impossible to effectively control the territory and protect biodiversity (poaching, illegal logging, etc.). Contamination by mines and explosive objects, disturbance of soil cover, and contamination by heavy metals still affect the ecosystems and will affect them in the future.

TREE SPECIES	OPACHYCHI FORESTRY	KOTOVSKE FOREST
	CURRENT ESTIMATE OF TIMBER VOLUME LOST (M³)	CURRENT ESTIMATE OF TIMBER VOLUME LOST (M³)
Pine (Pinus silvestris)	562,258	84,122
Pine (Pinus spp.)	12,957	-
Birch (Betula pendula)	9,536	831
Acacia (Robinia pseudoacacia)	418	-
Oak (Quercus rubra)	47	-
Pine (Pinus bancsiana)	445	-
Aspen (Populus tremula)	366	4
Oak (Quercus robur)	1,105	290
Adler (Alnus glutinosa)	1,032	24

Table 3. Volume of trees damaged or lost (cubic meters, m3) as result of the armed conflict in the Chornobylskyi REBR

3b. Desniansko-Starohutskyi National Nature Park

This park was founded on 23 February 1999 and is situated in the Sumy region's Seredyno-Budsky district, which is in the far north of Ukraine. Its area comprises 16,214.36 ha. In general, on its territory and in the adjacent regions of Novgorod-Severskyi Polissia, there are now 340 species of 37 rows of 6 classes [12]. The habitats of boreal species (Birds: Galliformes, Gruiformes, Falconiformes, Strigiformes, Piciformes, Passeriformes as well as numerous mammals: insectivores, rodents, lagomorphs, carnivorous mammals etc.), the majority of which are designated in the Red Book of Ukraine, are preserved in the protected area.

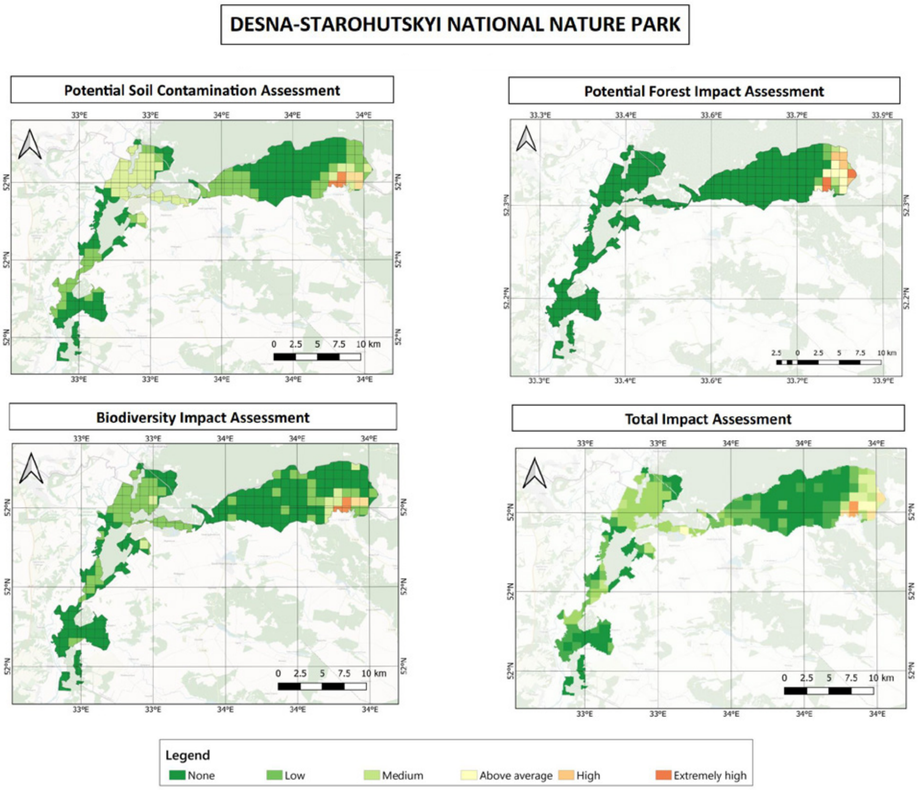

Figure 4. Desniansko-Starohutskyi National Nature Park

MILITARY ACTIONS

The case of the Desniansko-Starohutskyi NNP vividly demonstrates the challenge of bordering a significant part of the NRF object with the aggressor country. The length of the common border with Russia in the north and east reaches 30 km. The national park was not under occupation, but every day — starting from 24 February 2022 — it suffers from Russian shelling. The whole park was under regular artillery fire even after the liberation of the terrain. There were 13 war incidents within the Desniansko-Starohutskyi NNP (Znob-Novhorodska hromada) in the form of explosions due to shelling and artillery or missile attacks from 16 July to 9 November 2022. The central building of the park is located 400 m from the border with Russia. Every day, either the park itself, or the town of Seredyna-Buda, or the village of Stara Huta, where the institution's buildings are located, are under regular artillery fire. For example, on 31 July 2022, the Russians fired a mortar and damaged the new building of the Starohutske Nature Conservation Research Department, a forest fire monitoring tower, garages, a car, etc. After regaining governmental control, almost the entire area of the Desniansko-Starohutskyi NNP (about 98%) was recognized as the PMC zone stretching along the state border with the Russian Federation. In the Desniansko-Starohutskyi NNP, military artillery and missile attacks continue to affect the reserve. Part of the employees have been granted the right to work remotely, some are on layoff and unpaid leave abroad, and still others are mobilized. The overall damage, considering all types of military damage, affects more than 63% of all the grids analysed (Figure 4). The statistics indicate that biodiversity and soil damage were the most widespread, affecting over 40% of the grids.

IMPACTS ON SOIL

The Desniansko-Starohutskyi NNP faced mechanical and chemical pollution of the soil cover (Figure 4) caused by constant enemy bombardment involving the 122-mm howitzer D-30, 2S1 Gvozdika, 152 mm gun-howitzer D-20, and SO-152 barrel artillery (a projectile weighs 21.76–43.56 kg), which causes the formation of craters. All types of ammunition used in combat operations (high-explosive, fragmentation, armour-piercing, cumulative shells and mines) are characterized by the formation of a shock wave and explosion products that spread in the environment. When a projectile reaches an obstacle, the explosion and the formation of a shock wave occurs instantly in 10-4 to 10-5 seconds. The destruction radius increases with the mass of explosive in the projectile. For 122-mm and 152-mm shells with explosive weights of 4.5 kg and 8.4 kg, the radius of destruction in medium-density soil is 1.65 and 2.03 m respectively.
Explosive waves lead to the destruction of the sequence of soil horizons with an obvious disruption in the air-water regime. The soil at the impact site becomes turbulent, subjected to dynamic compaction, and contains numerous metal debris with remnants of explosive toxic substances. The main source of pollution during firing is explosion products, which are fine particles and ions of heavy metals that penetrate the soil.
The most common elements of military-technogenic origin in the study area were lead, zinc, vanadium, manganese, aluminium, iron, and sporadically copper. The total series of accumulation of gross forms of heavy metals in the interval of 0–10 cm were as follows: Zn > Pb > V > Mn > Cu. Zinc higher by 1.4 times is typical of the epicentres of artillery strikes, which is confirmed by the results of studies of paired sampling points. The zinc content in most of the samples exceeded the background level by 13 times and the MPC by 6.4 times. The lead content exceeded the background by 1.3–5 times and the MPC by 1.7 times at the site of the air strike on the Desna children's camp. A third of the samples collected showed an increased manganese content of 1.1 times.

IMPACTS ON FORESTS

The Desniansko-Starohutskyi NNP has also suffered significant losses of pine plantations as a result of an arson on the Russian side of the border (Table 3). In the Desniansko-Starohutskyi NNP in May 2023, 939.6 ha (6% of 16,214.36 ha in general) were burned due to the fire set on the Russian border.

TREE SPECIES	AREA, HA	N, COMPART.	TIMBER VOLUME, M³
Pine (Pinus silvestris)	816,751	377	307915,127
Birch (Betula pendula)	53,402	119	6354,838
Mixed forest	46,47	256	11896,32
Spruce (Picea abies)	2,338	400	935,2
Adler (Alnus nigra)	0,118	216	25,488

Table 4 . Area of forest loss in the Desniansko-Starohutskiy NNP

IMPACTS ON BIODIVERSITY

Regarding biodiversity, the park's administration did not provide precise data on the inventory of natural habitats and distribution of rare biota due to the lack of databases; therefore, the analysis used public data from biodiversity databases and standard data form of the Emerald Network, to which the park belongs (Site code: UA0000031).
Based on the results of the analysis, it can be assumed that the following natural habitats of Resolution 4 of the Berne Convention may have been adversely affected: D - Mires, bogs and fens: D5.2 - Beds of large sedges normally without free-standing water; E - Grasslands and lands dominated by forbs, mosses or lichens: E2.2 - Low and medium altitude hay meadows, E3.4 - Moist or wet eutrophic and mesotrophic grassland; G - Woodland, forest and other wooded land: G1.8 - Acidophilous Quercus-dominated woodland. The habitats, places of residence and migration and nesting places of a large number of species of rare avifauna and some mammals have been affected. A number of insects, amphibians, and fish have been affected indirectly.
It should be noted that part of the park's land is subject to withdrawal of a 2 km zone along the border to organize a border strip. Restricted access because of the border zone protection and organization of minefields will have a negative impact on biodiversity, especially on large carnivores and ungulates. On the other hand, due to the lack of economic activity in the recreational and economic zone, rare species, such as bears, are recorded more often. Detonations of animals using explosive devices have been recorded. Since hunting in the hunting grounds around the Desniansko-Starohutskyi park is banned, there is an increase in ungulates both on the territory of the NNP and in the adjacent areas. The main threat to biodiversity relates to the occurrence of fires, which

cannot be extinguished until the territory is cleared of mines.

Military activities have led not only to the death of forestry workers and destruction of the park's infrastructure, but also to a serious negative impact on natural complexes, especially forest habitats. In turn, significant military activities, partially limited access to park territories, and lack of monitoring data on biodiversity and natural habitats considerably underestimate the possible negative impact on the park's ecosystems.

3c. Hetmanskyi National Nature Park

The Hetmanskyi National Nature Park was established on 27 April 2009. The Hetmanskyi National Nature park is situated in Okhtyrka district in the southeast of the Sumy area. The Hetmanskyi NNP covers an area of 233.6 km² and stretches from the border with Russia to Poltava region borders. During the first five weeks of Russia's full-scale invasion of Ukraine, the territory of the Hetmanskyi NNP was the scene of fierce fighting between the Russian troops advancing on Kyiv through the Sumy region and the Defence Forces of Ukraine. The large part of it, including the administration in Trostianets, was under occupation. Even after the liberation of the park, part of its territory near the border with Russia has been under regular shelling. All this has caused damage to thousands of hectares of forests and other ecosystems within this NNP.

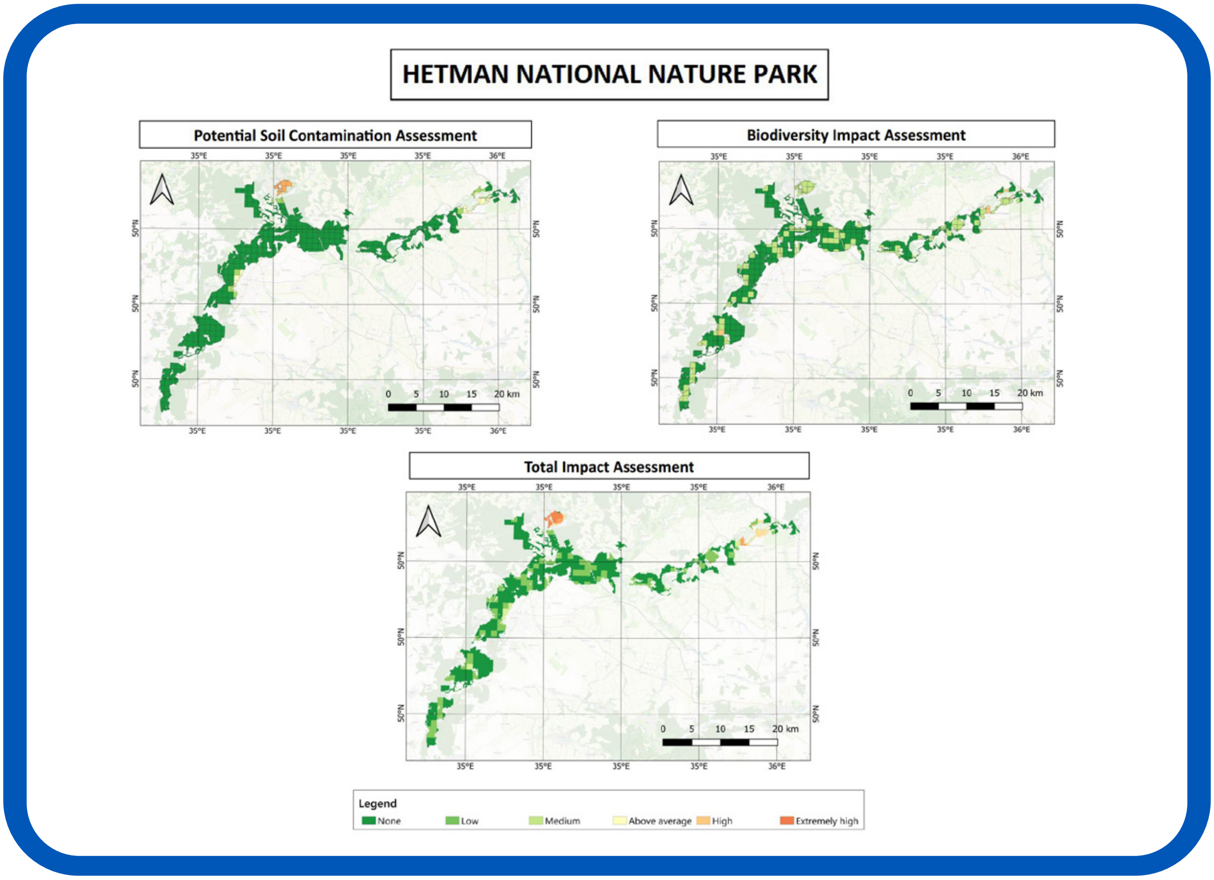

Figure 5. Hetmanskyi National Nature Park

MILITARY ACTIONS

About 46.3% of the Hetmanskyi NNP, that is ~11.000 ha, were under occupation between 24 February and early April 2022. The most active fighting took place in its eastern part, and the territories close to the border with Russia suffered the most negative impact. Areas bordering the settlements of Trostianets, Okhtyrka, and Velyka Pysarivka were particularly affected while facing active hostilities, direct clashes, artillery fire, aerial bombardment, and rocket attacks, which resulted in fires occurring both directly on the territory of the park and indirectly spreading to the forest lands of the park from settlements. According to official data, the territory of the park was completely liberated on 1 April 2022. Nearly 15% of the reserve was classified as PMC. In addition, an area of 12 ha within the Hetmanskyi NNP is defined as CMC according to official data. According to our results, the Hetmanskyi NNP had the highest war incidents level comparing with other analysed protected areas.

Similar to the other studied protected nature reserves mentioned above, formation of craters is typical of the Hetmanskyi NNP due to ammunition explosions and formation of pits and mound landforms related to fortifications.

Ammunition with gunpowder and explosives of different composition were used, and their combustion produced such substances as nitrogen, soot, hydrocarbons, lead, manganese dioxide, and other derivatives, which negatively affect the environment. In the areas of bombardment of the Hetmanskyi NNP, isolated exceedances of zinc by 1.4 times, vanadium by 1.9–2.5 times, and lead by 1.5–6.3 times were detected. Copper content exceeds the background level twice in the areas of air bombardment. For the areas of artillery shelling, copper content was recorded within the background values. In some samples, cadmium content is close to the MPC (0.5 mg/kg) but does not exceed it.

Disturbance of the soil and vegetation cover in some places was also significant because of the use of weapons and military equipment movement. Such military disturbances were most evident on dry sod-podzolic sandy soils of leveled terraces. Tracks and multi-track paths of significant depth were formed on the routes of military equipment movement; these often became filled with water, causing waterlogging of the terrain. Maintenance and repair of military equipment in field camps led to the area's pollution with fuels and lubricants, used oils, and antifreeze and organic solvents, Most often, in the places of significant spills of petroleum products in field filling stations, the soils lost their essential property — the ability to self-recover — while microorganisms were completely destroyed.

IMPACTS ON BIODIVERSITY

Due to the lack of databases, the NNP administration did not provide data on the inventory of natural habitats and distribution of rare biota; hence, we used public biodiversity and standard data form of the Emerald network, to which the NNP belongs.

Based on the results of the analysis, it could be assumed that the following natural habitats of the Resolution 4 of the Bern Convention may have been affected: D - Mires, bogs and fens: D5.2 - Beds of large sedges normally without free-standing water; E - Grasslands and lands dominated by forbs, mosses or lichens: E2.2 - Low and medium altitude hay meadows, E3.4 - Moist or wet eutrophic and mesotrophic grassland; G - Woodland, forest and other wooded land: G1.8 - Acidophilous Quercus-dominated woodland, G1.A1 - Quercus - Fraxinus - Carpinus betulus woodland on eutrophic and mesotrophic soils, G3.4232 - Sarmatic steppe Pinus sylvestris forests. Also, ichthyofauna of the Vorskla River was likely to be indirectly affected, namely the species included in the Red Book of Ukraine. Within meadow and forest habitats, insect habitats were negatively affected.

Despite the complete de-occupation of the park's territory, under the influence of mass mining, artillery, rocket attacks, deployment of the Armed Forces of

Ukraine, and possible re-invasion, the eastern part of the park, close to the borders, remains under attack.
The level of damage to the park ranges from None to Extremely High.
If soil damage was evident in 9.15% of the grid areas surveyed in this study, biodiversity damage was found in 24.89% of the grid areas (Figure 5). In the Hetmanskyi NNP, considering any type of damage, more than 27% of the grid areas surveyed in this study faced damage.

3d. Holosiivskyi National Nature Park

The Holosiivskyi NNP is the only one in Ukraine and one of the few national parks in the world located entirely within the boundaries of a city. It is located in the city of Kyiv, in its southern and western parts and, hence, faced a high pressure of recreational activities in the pre-war period. This park was established on 27 August 2007 by the Decree of the President of Ukraine and has a total area of 10,988.14 ha [39]. There are 23 endangered natural habitats requiring specific conservation measures on the territory of the Holosiivskyi NNP. It is divided into several relatively small, mostly wooded, areas. Herewith, the NNP has highly studied natural habitats and rare biota. Due to its bordering with settlements and frequent city dwellers' visits, there have been a lot of amateur observations, and, therefore, the total number of observations for the NNP's territory in the Global Biodiversity Information Facility (GBIF) database accounts for about 15,000 records.

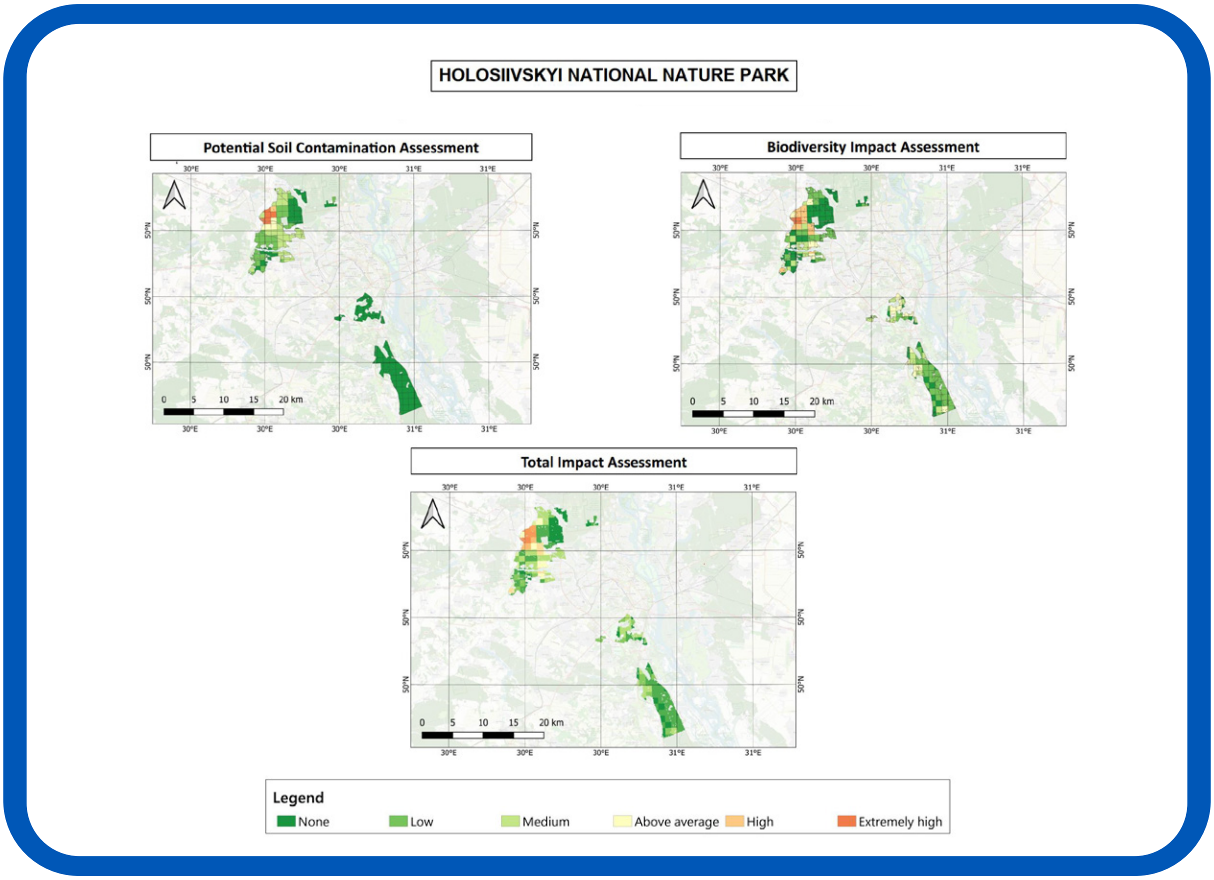

Figure 6. Holosiivskyi National Nature Park

MILITARY ACTIONS

The north-western part of the park suffered the greatest negative impact during the occupation of the cities of Hostomel, Bucha, and Irpin, which directly borders the NNP's territory. As part of the offensive on Kyiv, Russian troops tried to surround and besiege the Ukrainian capital Kyiv from the west. Columns of Russians moved from the territory of Belarus through Chornobyl. As a result, areas on the border of the NNP were most affected. For the Holosiivskyi NNP, a rather high war incident density was revealed. On the other hand, only 0.3 % of the entire Holosiivskyi NNP territory (34 ha) was classified as PMC, which is the lowest level among the protected nature reserves studied.

IMPACTS ON SOIL

Along with territory mining, the Holosiivskyi NNP faced a mechanical impact, namely deformation of the soil cover due to the construction of defence infrastructure. During the battles, the 85-mm divisional gun D-44, 122-mm howitzer D-30, and 152 mm gun-howitzer D-20 weapons were used for direct fire artillery, involving high-explosive incendiary and high-explosive anti-tank projectiles weighing from 6.5 to 43.56 kg.
At the depth of up to 1.5 m, soil homogeneity disturbance was recorded on the military operations territories. Following the disturbance of genetic horizons of the soil cover, plants' adaptation to climate change have weakened, arid conditions worsened, and the lack of moisture increased. This has intensified a number of hazardous geomorphological processes, including landslides, soil subsidence, etc. When constructing fortifications, the Ukrainian military disregarded the groundwater depth and soil moisture conditions, which negatively affected the landscapes of the nature conservation area. Part of the NNP, namely Pushcha-Vodytsia Forest, was shelled, which caused soil deformation in all directions of the shock wave propagation. As for soil pollution with heavy metals, only manganese exceeded the background level by 1.5–2.1 times, while the rest of the studied elements are within the background levels.

IMPACTS ON BIODIVERSITY

For sites with Above Medium to Extremely High biodiversity damage, the following types of natural habitats faced moderate negative and negative impacts (Resolution 4 of the Bern Convention): C - Inland surface waters: C2.33 - Mesotrophic vegetation of slow flowing rivers; G - Woodland, forest and other wooded land: G1.1 - Riparian and gallery woodland, with dominant Alnus, Betula, Populus or Salix, G1.7 Thermophilous deciduous woodland.
In these areas, habitats and places of migration, reproduction, and feeding of a number of species included in national and international nature lists faced a moderate negative and negative impact.
Considering all types of damage, more than 72% of the grid areas surveyed in the NNP suffered damages (Figure 6). Soil quality was affected in about 60% of the surveyed grids. Biodiversity was affected in about 40% of the surveyed grids. The damage levels for soil and biodiversity range from 0 to 5. The mean values for damage_bio and damage_soil are 0.73 and 1.17, indicating that biodiversity damage was more significant than soil damage. There was a moderate positive correlation (around 0.53) between soil and biodiversity damage. This suggests that areas with higher soil damage were likely to have higher biodiversity damage as well.

To sum up, the difficulty of assessing environmental impacts caused by military actions in the north of Ukraine regards critical causal relationships.

First of all, data on the state of pre-war (until 24 February 2022) biodiversity within the Desniansko-Starohutskyi NNP and the Hetmanskyi NNP are incomplete. Even where such information is available (the Chornobylskyi REBR and the Holosiivskyi NNP), it is either significantly fragmented or lacks proper spatial (geocoded) distribution, which considerably reduces its value. Secondly, the reconstruction of environmental losses caused by hostilities using incomplete previous and actual data (due to limited access related to unexploded ordnance or mines) is a difficult and sometimes impossible task. Now, only a general assessment of changes in landscape structure, including vegetation cover, can be considered. Thirdly, direct factors induced by hostilities should be ranked in descending order: fires (spreading over large territories) — combat clashes (moving the front line to considerable distances) — landmine pollution (covering certain limited territories) — fortifications (separate localities) — chemical, including radiation, pollution in places of projectile ruptures (point spreading). Such ranking mainly relates to the studied area and the extent of radical ecosystem transformations caused by specific factors. Based on this approach, it is possible to roughly estimate changes in landscape structure, changes in structural and functional diversity in damaged ecosystems, release of carbon deposited in forest ecosystems (extrapolating this to climate change), direction of successional processes, and possibility of alien species invasion. In general, all these assessment objects are causally interrelated.
Hostility-induced **indirect factors**, such as destruction or damage of infrastructure, significant shortage of financial support and income, and reduction in the number of employees (due to military obligation and forced migration), also affect the ability of nature conservation.

Military actions:

- **Mining of 4 territories more than 2,5 times bigger compared to Berlin**
- **Fires caused by artillery shelling and purposeful setting of fires in forested areas: 14% of Chornobyl REBR and 6% of Desniansko-Starohutskyi**
- **Remote violence: artillery, avia missile attacks (shells with a weight of 6.5 to 43.56 kg), drones**
- **Military occupation of the land: 94% of Chornobyl REBR and 46.3 % of Hetmanskiy NNP: the movement and maintenance of military vehicles and machinery, fortification.**
- **Armed clashes between opposing armed forces.**

The choice of restoration measures requires a comprehensive consideration of a set of various factors. The key factors include the potential ability of technology to reduce the damage, costs to carry out the process, technology availability and readiness to use it, impact on the environment, duration of the process, and public opinion [53].
Potential long-term impact on the environment depends on multiple factors, e.g. climate, geographical zone, duration of war, types of habitats, type of impacts, etc. In the South Caucasus, Bosnia, or Croatia, much of the areas still suffer from substantial landmine contamination [7].
After the war in the basin of the Northern Al-Kabeer river in Syria, the impact was significantly negative and led to a more than 10-fold increase in erosion in steep areas, mainly as a result of forest fires [2]. In the Sabah Al-Ahmad Nature Reserve of Kuwait, even 10 years after the severe damage caused by military activities, soil natural recovery did not result in the full restoration of land to its pre-disturbance levels, even though the studied reserve was protected from human activities during the post-liberation period and cleared of mines and ammunitions [41]. The effects of armed conflicts on land systems over longer time periods remain under-studied and require interdisciplinary research efforts, bringing together geography, environmental sciences, political sciences, and anthropology [7]. The findings by Broomandi et al. (2017) revealed a possible correlation between the degree of anthropogenic soil pollutants and the remains of the Iraq-Iran war after 25 years [8].

Based on previous experiences and our research results, we would recommend such measures as:

1. Monitoring of impact dynamics can encourage decision-makers and planners to take respective priority conservation actions, thereby reducing land loss and degradation issues [2]

2. Active restoration programme after the end of military actions is needed to restore the soil, forests, and biodiversity as natural recovery may not result in full restoration [41].

With regard to the Chornobylskyi REBR, Desniansko-Starohutskyi NNP, and Hetmanskyi NNP, all the restoration efforts should start with mining clearance as most of their territories contain land mines, which limit not only impacts assessment on-site but also the implementation of any recovery measures. Access to the territories is crucial to be able to develop a system of measures for soil cleaning. At the same time, impact identification requires proactivity and commitment from those stakeholders who are interested in management of preservation areas, expert involvement in analysing the soil, and military personnel guaranteeing the safety of experts working on the impact of military actions.
Of the broad range of available methods and techniques, we selected the most suitable ones for the studied areas when considering mapped military actions and identified damage. Analyses were performed using the VOSviewer software, taking into account 658 peer-reviewed sources. The bibliometric analyses results are presented in Tables 5, 6, and 7.

Solutions for the Restoration and Protection of Soils in the Studied Territories

In the course of soil restoration, it is necessary to primarily ensure the safety of the studied areas. Restoration of the soils of the territories that have faced military actions involves the development of complex restoration measures by reclamation of craters, trenches, and ditches, followed by the establishment of vegetation cover, rewilding, and, in some cases, conservation of the most polluted soils. Restoration of vegetation cover is best achieved through the natural processes of colonization by species from surrounding ecosystems. Additional measures are recommended for a more effective restoration of the vegetation cover, in particular, sowing of seed mixtures based on perennial species of local flora. Plant cover restoration requires constant monitoring to prevent the appearance of unwanted (invasive) species and formation of low-value plant communities.
Soil erosion caused by fires is the most obvious environmental disturbance, because by reducing or eliminating vegetation and ground cover, fires

SOIL EROSION RATE ASSESSMENT → SOIL CONTAMONATION ANALYSES → DEVELOPMENT OF COMPLEX RESTORATION MEASURES → RECLAMATION OF CRATERS, TRENCHES, DITCHES → PHYTOREMEDIATION AND ESTABLISHMENT OF VEGETATION COVER → CONTROL MEASURES AND ACCELERATION OF VEGETATION COVER RESTORATION → MONITORING OF VEGETATION COVER.

make the soil more susceptible to raindrop impact, reducing aggregate stability and promoting sediment detachment [58]. There are some emergency stabilization treatments, such as mulching and seeding, that provide an immediate ground cover to reduce soil erosion and preserve nutrients. For long term soil treatment, it is necessary to conduct soil erosion rate assessment [11, 55, 58] in order to find the right methods for soil remediation.

The main petroleum products that have entered the ecosystem because of military operations are diesel fuel, heating oil, and lubricants. A particularly difficult contaminant to deal with is diesel oil as it consists of many compounds of different chemical structures and biodegradability. Diesel oil is characterised as a low evaporation rate liquid with slow degradation rates compared to other petroleum derivatives. Each of diesel oil compounds has a different impact on soil microorganisms. All petrochemicals have strong toxic, carcinogenic, and mutagenic properties. For environmental restoration, many remediation technologies have been developed and applied — biodegradation, advanced oxidation process (AOP), and many combined methods [49, 52]. One of the promising technologies with many advantages, such as suitability to various types of pollutants, short treatment period, high efficiency, and technical simplicity, is thermal desorption. In fact, though, in comparison with physicochemical methods (application of skimmers, booms, barriers and sorbents, dispersants, and controlled in situ burning), bioremediation is a more effective approach that does not disrupting the polluted environments.

Bioremediation as an economical and environmentally friendly approach is based on microorganism's capabilities to degrade petroleum hydrocarbons. This method aims at biostimulation and bioaugmentation of the natural attenuation of the contaminants with indigenous microorganisms [5]. Novel approaches to bioremediation, including addition of novel materials, using GEMs, and integration of electrochemical strategies with biological methods, could be very effective for remediation of a damaged area.

A significant part of the territory of Ukraine occupied by Russia remains mined. The number of shells that Russia has used in the course of its military action against Ukraine is unprecedented. All this naturally led to a large-scale soil contamination with heavy metals. Numerous studies have shown that the latter are extremely persistent in the environment and not biodegradable [16, 35]. High amounts of heavy metals in the environment are toxic for most organisms and thus limit an acclimation of vegetation and natural succession in contaminated areas.

Heavy metals strongly affect the biological properties of soils. The activity of soil enzymes is a sensitive indicator of soil quality [63] and is hence proposed as a reliable tool to monitor changes in soils [29]. The extent and degree of heavy metal contamination should be considered before selecting remediation methods for affected soil areas. For example, it has been found that some plant species, like Platanus orientalis, Robinia pseudoacacia and Fraxinus rotundifolia, are capable of accumulating substantial amounts of heavy metals in their tissues [42, 43]. To quantify the ability of plant tissues, particularly foliar tissues, to accumulate heavy metals, a metal accumulation index (MAI) has been developed [32]. Recently, using 24 species of trees, 33 species of plants, and 20 species of flowers, the phytoremediation of the main heavy metals, namely arsenic, lead, cadmium, nickel, mercury, iron, copper, and zinc, has been comprehensively studied [48]. The results are very promising and can help environmental officials and governments to find a sustainable solution to get rid of heavy metals hazardous for ecosystem.

Another method is an artificial restoration through the application of nitrogen (N) and phosphorus (P). This method can conserve plant diversity in contaminated soils and accelerate the recovery of polluted ecosystems. It is inexpensive and convenient, can increase the resistance of plants to adversities and promote the growth of plants in heavy metal polluted soils [23]

METHODS AND TECHNIQUES	ADVANTAGES AND DISADVANTAGES
Land mines: lead to soil contamination and endanger the lives of human beings and animals.	
• Demining/mining clearance: excavators, flails • Mine defusal	**ADVANTAGES** • Responsible mining clearance conducted by experts and military personnel can protect the population and preserve a park's biodiversity. **DISADVANTAGES** • Exploding mines intentionally could lead to increased military waste and soil contamination, compression, and erosion.
Military waste and soil contamination (heavy metals, oil spills, shelling) lead to the loss of nutrients, mineral composition, and soil biodiversity.	
• Military waste removal by specialised organisations and military personnel • Soil detoxification • Biological treatment/ bioremediation • Chemical treatment • Physical treatment	**ADVANTAGES** • Fast soil analysis and military waste removal can help to mitigate the possible long-term impacts of military waste. • Detoxification of soil can make the environment cleaner and safer for plant, animal, and human life by removing harmful contaminants. • Biological, chemical, and physical treatments can bring back nutrients and soil biodiversity. **DISADVANTAGES** • Soil detoxification: it could be expensive and take some time to fix the problem, depending on the type of contamination. • Bioremediation: after partial biological processing, additional detoxification approaches may be needed due to increased toxicity. • Physical treatment: it may involve high investments, destruction of soil structure, risk of secondary pollution, and risk of destruction of nutrients and disturbance of soil properties. • Chemical treatment: chemical treatment residues have a significant influence on the ecological system, soil fertility reduction, and underground water contamination, affecting animals and birds and promoting serious environmental pollution.
Land surface change: soil compression, erosion, craters, trenches, construction of bunkers, etc.	
• Loosening compacted soil: aeration, introducing gypsum (clay) and organic matter. • Trenches and damage caused by bombing: cover • Erosion: replanting vegetation suited to site conditions.	**ADVANTAGES** • Aeration and gypsum (clay) loosen the soil, allowing water, air, and nutrients to reach the roots and be absorbed. **DISADVANTAGES** • Aeration: high energy consumption and maintenance costs, can have an erosive effect. • Gypsum (clay): may result in decreasing potassium or magnesium levels in the soil. • Excessive organic matter can lead to nitrogen tie-up.

Table 5. Examples of measures to address military actions impacts on soil

Solutions for the Restoration and Protection of the Studied Forests

The primary stage of the restoration of forests affected by military actions is the assessment of their condition and the establishment of a monitoring system. Due to existing dangers, conducting research, monitoring, and any recovery measures is impossible without ensuring the territory's safety; hence, the territory's demining is a prerequisite. Any studies should take place without a threat to the life of researchers.

The first step in the restoration of forests is planning — creation of a strategy for their restoration with a scheme of restoration measures and their phased implementation. The key approach to reforestation is natural succession, which is considered the most desirable way of reforesting naturally protected areas. Complementing these stands with valuable forest-forming species will allow the creation of mixed semi-natural forests constituting a highly stable forest ecosystem. Thus, the formation of natural and semi-natural mixed forests is the most effective way to restore the forests of protected areas. The next step is to support and accelerate the natural recovery process by implementing planned forest ecosystem management measures. Newly formed forests need constant assessment and monitoring. Another important component is social forestry involving local communities in forest restoration, as well as support for community initiatives on forest restoration.

Restoration of forest landscapes after fires caused by combat operations is a complex and multi-stage process. It is complicated by the high probability of finding various explosive devices (unexploded shells, anti-tank and anti-personnel mines, etc.) on the territory. There is virtually no experience of such measures in global practice. Traditionally, the restoration of forest landscapes after fires involves several sequential phases: planning, design, implementation, monitoring, and evaluation. Active, passive, and mixed management are the key strategies for restoring forest landscapes.

Active management typically includes sanitary logging, anti-erosion strengthening of slopes, creation of forest cultures, and maintenance logging. Passive restoration methods involve ensuring natural succession with gradual restoration of the original type of forests. Mixed methods regard the promotion of natural regeneration of forests on burnt areas by seeding or replanting local species of trees and shrubs, as well as maintenance logging. Each of these strategies has both strengths and weaknesses. Active management assumes a relatively shorter recovery period and rapid economic returns; however, it is initially very resource-intensive, while forest plantations formed in this way have low biodiversity and are vulnerable to biological invasions and climate change. Passive management, on the contrary, requires minimal economic costs, but its restoration of forest ecosystems and functional biodiversity is very time-consuming. The mixed methods of reforestation on burned areas are, by all indicators, in the middle.

Assessing the success of forest landscapes' functioning after the fires caused by military activities is an extremely complex task that requires consideration of not only environmental or forestry aspects, but also economic and social impact. The effectiveness of forest restoration monitoring can be assessed by remote sensing of the Earth, which, however, requires adequate criteria to avoid data duplication and misinterpretation. The economic and social aspects regard the assessment of the mentioned territories' use and benefits received by local communities.

Any work in forest ecosystems should be conducted only after clearance by the authority responsible for demining. However, the demining process will first take place in settlements, on the roads, agricultural fields, etc., while forests are currently not a priority. Therefore, training forest workers at all enterprises in liberated areas on safety requirements is needed.

Updated management policies incorporating proactive management of fire risks and shifting focus from common dense and highly flammable coniferous monocultures to more structurally diverse and less flammable forests could be a crucial solution. Establishment of mosaic plantations of varying densities (from typical high-density plantations to widely spaced structures) and controlling tree density and forest edges could also be important elements of new management policies. Meanwhile, considering

the mine pollution of the territory, especially within the protected nature reserves, the use of active and mixed management of forest landscape restoration is extremely challenging. This is primarily related to employee safety and the need for demining. The most adequate method is, therefore, that of passive forest restoration, which is based on natural successional processes.
Due to mining and shelling, it is impossible to carry out necessary measures to prevent forest fires and protect forests against pests and diseases. Forest fragmentation caused by war-related disturbances leads to the loss of biodiversity and forest ecosystem services [14]. Some forest ecosystems cannot be restored (e.g. burned relict forests, lost nestling places, or rare species). Long-term monitoring of damaged areas using field inventories (where possible) and remote sensing tools are promising methods. Remotely sensed data provide strong support to future forest planning in Ukraine that should account for the landscape-level distribution of fuels, risk of uncontrolled fire spread, and UXO contamination.

ASSESSMENT AND MONITORING → DEVELOPMENT OF RESTORATION MEASURES → REFORESTATION IN A NATURAL WAY WITH THE ADDITION OF VALUABLE REFORESTATION SPECIES → CONTROL AND ACCELERATION OF THE RESTORATION PROCESS → FOREST MONITORING

METHODS AND TECHNIQUES	ADVANTAGES AND DISADVANTAGES
Forest contamination by mines and explosive objects (UXO)	
• **Licensed trainings to involve foresters in the demining process.** • **List of detailed recommendations, which should be mandatory and applied on liberated territories.**	**ADVANTAGES** • Greater awareness among foresters about land-contamination risks. **DISADVANTAGES** • Forests are currently not a priority for demining. • Demining in forests is more difficult than in other territories, the usage of special machines is limited. • Lack of experienced staff and proper equipment for forest demining.
Fires	
• **Fire suppression operations.** • **Satellite-based approach to map forest disturbances (e.g. fires or tree harvesting).** • **Updated management policies incorporating proactive management of fire risks.**	**ADVANTAGES** **Lower vulnerability of forests.** • Satellite data sources sufficiently provide the long-term data on forest disturbance regimes. • Forests become less flammable due to more structurally diverse polycultures and mosaic plantations of varying densities. **DISADVANTAGES** • Ongoing battles and mines and UXO contamination make it impossible to restore forests or even prevent forest fires. • Difficulties with compiling and comparing forest fires statistics between different actors due to the different techniques used (e.g. satellite vs ground data).
Forest fragmentation caused by war-related disturbances	
• **Large-scale damaged forest cover mapping.** • **Satellite data for assessment of damaged forests.** • **Restoring of damaged forests.** • **Developing capacities for growing planting forest material.**	**ADVANTAGES** • Fragmented forests could reduce fuel contiguity that facilitate rapid fire spread. **DISADVANTAGES** • Complex restoration and rehabilitation are needed. • Detailed assessment is needed. • Some forest ecosystem cannot be restored. • Spatial data is not always accurate and up-to-date.
Absence or violation of the monitoring system of damaged forests	
Development of forests monitoring system and assessment methodology (field inventories combined with remote sensing). • **Digitalization of forest management.**	**ADVANTAGES** • Remotely sensed data provide strong support to future forest planning in Ukraine. **DISADVANTAGES** • Part of the protected territories and objects are still located in the combat zone, while liberated areas face forest contamination; therefore, field inventories are dangerous or impossible.

Damaged forest infrastructure	
• Conducting an inventory of destroyed and damaged objects of forest infrastructure. • Development of ecological tourism and recreational use of forests.	**ADVANTAGES** **Rebuilding of forest infrastructure will support ecosystem restoration, increase financial income from recreation, tourism, and forestry, and support research, monitoring, and climate change adaptation.** **DISADVANTAGES** • Ongoing battles, mines, and UXO contamination make it impossible to restore forest infrastructure. • Limited financial support from the state budget.

Table 6. Examples of measures to address military actions impacts on forests

Solutions for the Restoration and Protection of Biodiversity of the Studied Territories

Following the completion of demining operations and the restoration of territorial security, the establishment of a comprehensive monitoring framework is imperative to assess the status of local species populations and to collect data on biodiversity within protected areas. Subsequent phases entail the rehabilitation of habitats, prioritizing specific taxonomic and ecological groups within the biota. In instances of severe degradation, conservation efforts, followed by habitat restoration, are deemed necessary. Of exceptional importance is the preservation of indigenous species populations, particularly those of high value and rarity, alongside stringent measures to mitigate the proliferation of invasive species. Where feasible, initiatives for artificial breeding and reintroduction programs for species affected by conflict are advocated, aimed at restoring them into their natural habitats. Research efforts are vital to elucidate the consequences of war for both plant and animal populations, while continual monitoring and evaluation of biodiversity post-recovery dynamics are mandatory. Expansion of protected area boundaries is warranted to encompass vital habitats, further safeguarding biodiversity. Concurrently, engaging local communities through environmental protection and educational initiatives is crucial for fostering stewardship and promoting sustainable practices.

MONITORING OF LOCAL SPECIES POPULATIONS AND COLLECTING BIODIVERSITY DATA → RESTORING HABITATS → SUPPORTING POPULATIONS OF ABORIGINAL, VALUABLE, AND RARE SPECIES → MONITORING AND ASSESSING BIODIVERSITY DYNAMICS AFTER RESTORATION → DEVELOPING MEASURES TO RESTORE BIODIVERSITY OF TERRITORIES AFFECTED BY MILITARY ACTIONS → EXPANDING PROTECTED AREAS → CONDUCTING NATURE PROTECTION AND EDUCATIONAL EVENTS INVOLVING LOCAL COMMUNITIES.

Changes in the structure of landscapes in all four studied areas depend on the type of lands where combat clashes took place and/or permanent or temporary fortifications were built. In particular, two groups of landscapes with different degrees of vulnerability should be distinguished: 1) forest and 2) non-forest ones. The impact of combat-induced fires on these landscapes is fundamentally different. While fires in non-forest landscapes (meadows, fallows, floodplains, etc.) have a very short-term effect, mainly determined by one growing season, it is long-term in forest landscapes and can manifest itself over the next several decades. Structural and functional diversity changes are primarily related to the structure of landscapes where hostilities took place. Structural diversity determines the availability of ecological niches in ecosystems, while functional diversity determines the effectiveness of energy transmission and ecosystem resilience [31]. The non-forest landscapes' damage had a minor effect on the structural and functional diversity of open ecosystems (meadows, wetlands, floodplains, and fallows), which faced no major changes and recovered during the growing season of 2022. Perhaps the most significant (positive) impact on them involved a sudden release — due to fires — of ash elements, which were absorbed by the plant biomass in the same growing season. Fires in forest landscapes significantly affected both structural and functional diversity, as habitats formed by perennial biomorphs, such as trees, were destroyed. The loss of these habitats primarily affects forest biota, particularly saproxylic and xylobiont animals and fungi. Restoring forest ecosystems' structure and functionality will take several decades and involve serious successional changes on the damaged territory.

In addition to the loss of diversity, special attention should be paid to the organization of monitoring of alien species and, first of all, plants, since it is highly probable that the occupation army, on its equipment and personnel's clothing, brought the seeds of alien plants, the species distribution of which, for example, may be limited to Eastern Siberia, Altai, the Urals, etc. In the studied protected natural areas, detailed monitoring of the ruderal flora should be organised along the routes of the Russian army's invasion, especially in places of fortifications and long-term parking of both equipment and personnel.

Data collection for biodiversity restoration provides baseline information and enables monitoring of progress, supporting informed decision-making and efficient resource allocation. Additionally, it fosters community engagement and supports policy development, enhancing long-term planning and collaboration in restoration efforts. In mining clearance, clearance programs that facilitate environmental enhancement through land restoration and sustainable land use practices should be prioritized.

Pollution cleanup and prevention, as well as restoring soil health, are critical aspects of ecological restoration, ensuring the health of ecosystems and the well-being of surrounding communities.

Developing crisis response plans for wildlife is highly important for mitigating the impact of emergencies and ensuring prompt and effective actions to protect and preserve vulnerable species and their habitats.

Thus, there are many methods of ecosystem restoration, but the strategy and tactics must be developed on a case-by-case basis. It is necessary to conduct field studies after the end ofactive military actions, determine the extent of damage to ecosystems, and, based on the data obtained, develop a system of restoration and long-term monitoring. The current study can help environmental officials and governments find a sustainable solution to dispose of heavy metals hazardous to ecosystems.

METHODS AND TECHNIQUES	ADVANTAGES AND DISADVANTAGES
Ecosystem contamination by mines and explosive objects (UXO)	
• **Demining/mining clearance.** • **Mine defusal.**	**ADVANTAGES** • Any work in ecosystems should be conducted only after clearance and demining. **DISADVANTAGES** • Risk of cratering and pollutants released from onsite detonation of mines. • The possibility of using special machines for the disposal of explosive devices is limited in some of the ecosystems. • Climate change and climate-related hazards should be considered.
Absence or violation of the monitoring system of the damaged ecosystem	
• **Remote environmental monitoring and assessment in near real-time.** • **Mapping the damage to designated natural areas and reserves.** • **International cooperation.**	**ADVANTAGES** **Analysis and assessment in line with the needs of the area. Mapping should identify immediate priorities where restoration should be fast-tracked due to the high risks, such as significant threats to biodiversity, climate, or ecosystems, in order to develop a strategic plan to guide overall restoration.** • Data could be used for international cooperation, technical assistance, and financial support. **DISADVANTAGES** • On-side access is limited due to the presence of UXO or the proximity to frontlines. • Remote data has limitations and can both guide and be enhanced by field data collection. • Monitoring system needs experts to plan and implement environmental policies.
Biodiversity loss, animal migration, microbiome compromise, and habitat destruction	
• **Pollution cleanup and prevention.** • **Computer modelling.** • **Habitat restoration and conservation.**	**ADVANTAGES** • Habitat restoration and conservation support the mitigation of damages and prompt effective actions to protect and preserve vulnerable species and their habitats. **DISADVANTAGES** • Limited on-site access. • Lack of knowledge about biodiversity restoration approaches in the special case of war impacts. Habitat restoration projects can be expensive and may take years to show significant results. • Restored habitats could be vulnerable to invasion by non-native species. • Fragmentation of habitats can limit the effectiveness of restoration efforts, especially for species that require large, interconnected habitats.

Table 7. Examples of measures to address military actions impacts on biodiversity

NATURE PROTECTED AREA:

CHORNOBYLSKYI RADIATION AND ECOLOGICAL BIOSPHERE RESERVE

Covering more 230 thousand ha. On its land, there is a large deal of diversity, including 23 terrestrial, 7 aquatic phytosystems, 5 distinct landscapes, 120 species of lichens, 200 species of mosses, 303 species of vertebrates, and 1256 species of higher plants.

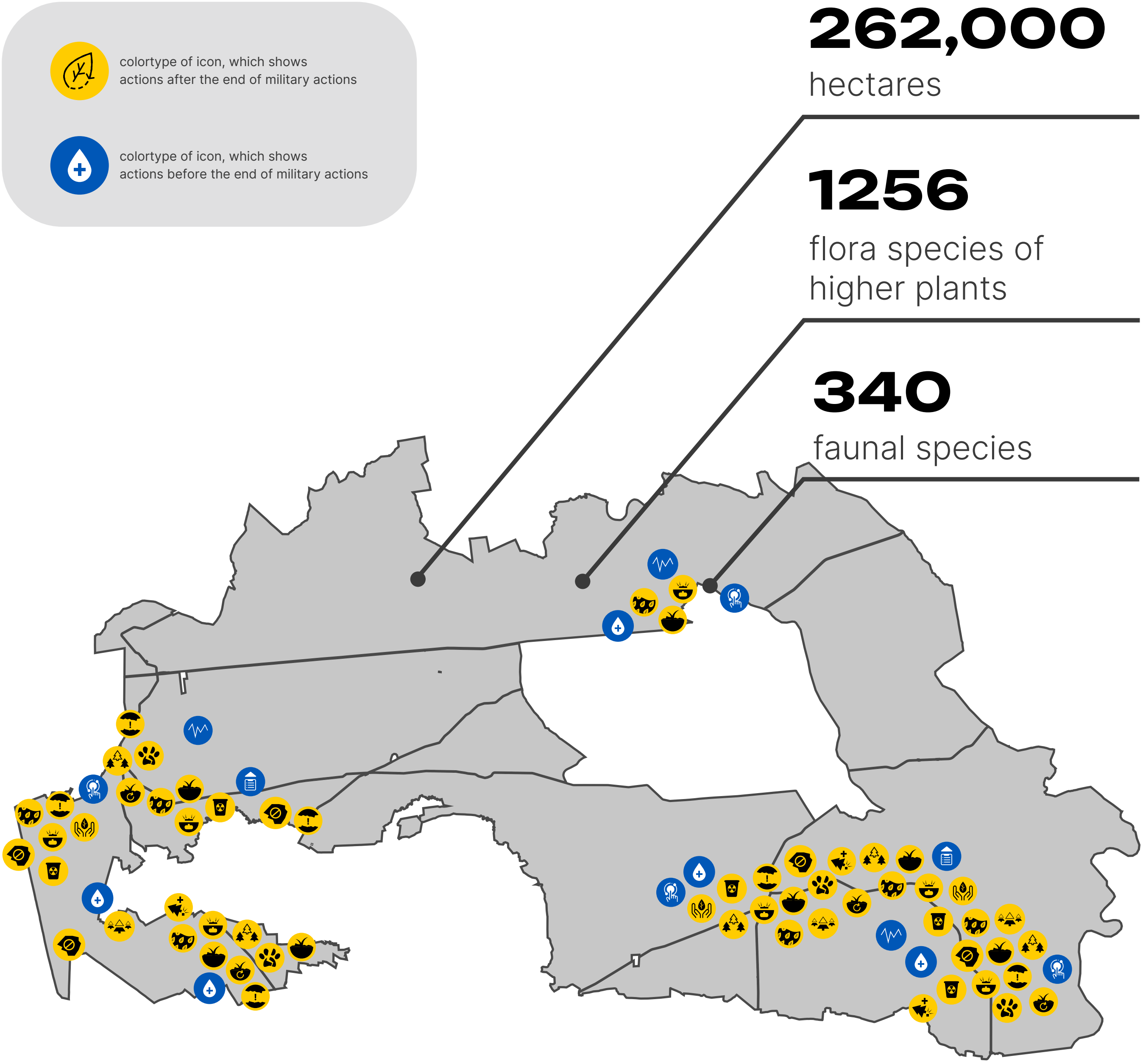

Figure 3. Chornobylskyi Radiation and Ecological Biosphere Reserve

ACTION PLAN:
BEFORE THE END OF MILITARY ACTIONS

- MONITORING AND RISK ASSESSMENT
- EMERGENCY STABILIZATION TREATMENTS
- DIGITALIZATION AND MAPPING OF THE PROCESSES OF MONITORING
- RESTORATION MEASURES PLANNING

ACTION PLAN:
AFTER THE END OF MILITARY ACTIONS

- DEMINING AND ENSURING THE SAFETY OF THE TERRITORY
- REFORESTATION
- MILITARY WASTE REMOVAL
- NATURAL SUCCESSION
- MONITORING OF TERRITORIES THAT WERE INACCESSIBLE
- FORMATION OF MIXED SEMI-NATURAL FORESTS
- RECLAMATION OF DESTROYED SOIL COVER
- CONTROLLING TREE DENSITY
- ESTABLISHMENT OF VEGETATION COVER
- REHABILITATION FOR BROKEN CROWNS AND TREE FALLS
- REWILDING
- DEVELOPING CRISIS RESPONSE PLANS FOR WILDLIFE
- ACTIVE SOIL RECOVERY IS LIMITED
- HABITAT RESTORATION AND CONSERVATION

NATURE PROTECTED AREA:

DESNIANSKO-STAROHUTSKYI NATIONAL NATURE PARK

Its area comprises 16,214.36 ha. There are 340 species of 37 rows of 6 classes.
The habitats of boreal species (birds: Galliformes, Gruiformes, Falconiformes, Strigiformes, Piciformes, Passeriformes; mammals: insectivores, rodents, lagomorphs, carnivorous)

colortype of icon, which shows actions after the end of military actions

colortype of icon, which shows actions before the end of military actions

16214.36
hectares

801
Flora species of higher vascular plants

340
faunal species

ACTION PLAN:

BEFORE THE END OF MILITARY ACTIONS

- DIGITALIZATION AND MAPPING OF THE PROCESSES OF MONITORING
- RESTORATION MEASURES PLANNING
- EMERGENCY STABILIZATION TREATMENTS

Figure 4. Desniansko-Starohutskyi National Nature Park

ACTION PLAN:
AFTER THE END OF MILITARY ACTIONS

- DEMINING AND ENSURING THE SAFETY OF THE TERRITORY
- MILITARY WASTE REMOVAL
- ON-FIELD MONITORING OF TERRITORIES
- SOIL RESTORATION
- DETOXIFICATION
- SOIL EROSION RATE ASSESSMENTS
- ANTI-EROSION MEASURES
- RESTORATION OF VEGETATION COVER
- COLONIZATION OF SPECIES FROM SURROUNDING ECOSYSTEMS
- LOOSENING COMPACTED SOIL
- BIOLOGICAL, CHEMICAL AND PHYSICAL TREATMENTS
- REFORESTATION
- FORESTS MONITORING SYSTEM
- SHIFT TO MORE STRUCTURALLY DIVERSE AND LESS FLAMMABLE FORESTS
- ESTABLISH OF MOSAIC PLANTATIONS
- REHABILITATION FOR BROKEN CROWNS AND TREE FALLS
- HABITAT RESTORATION AND CONSERVATION
- SUPPORT OF POPULATIONS OF ABORIGINAL, VALUABLE AND RARE SPECIES
- MONITORING AND ASSESSMENT OF BIODIVERSITY DYNAMICS AFTER RESTORATION

NATURE PROTECTED AREA:

HETMANSKYI NATIONAL NATURE PARK

Hetmanskyi NNP covers an area of 233.6 km²

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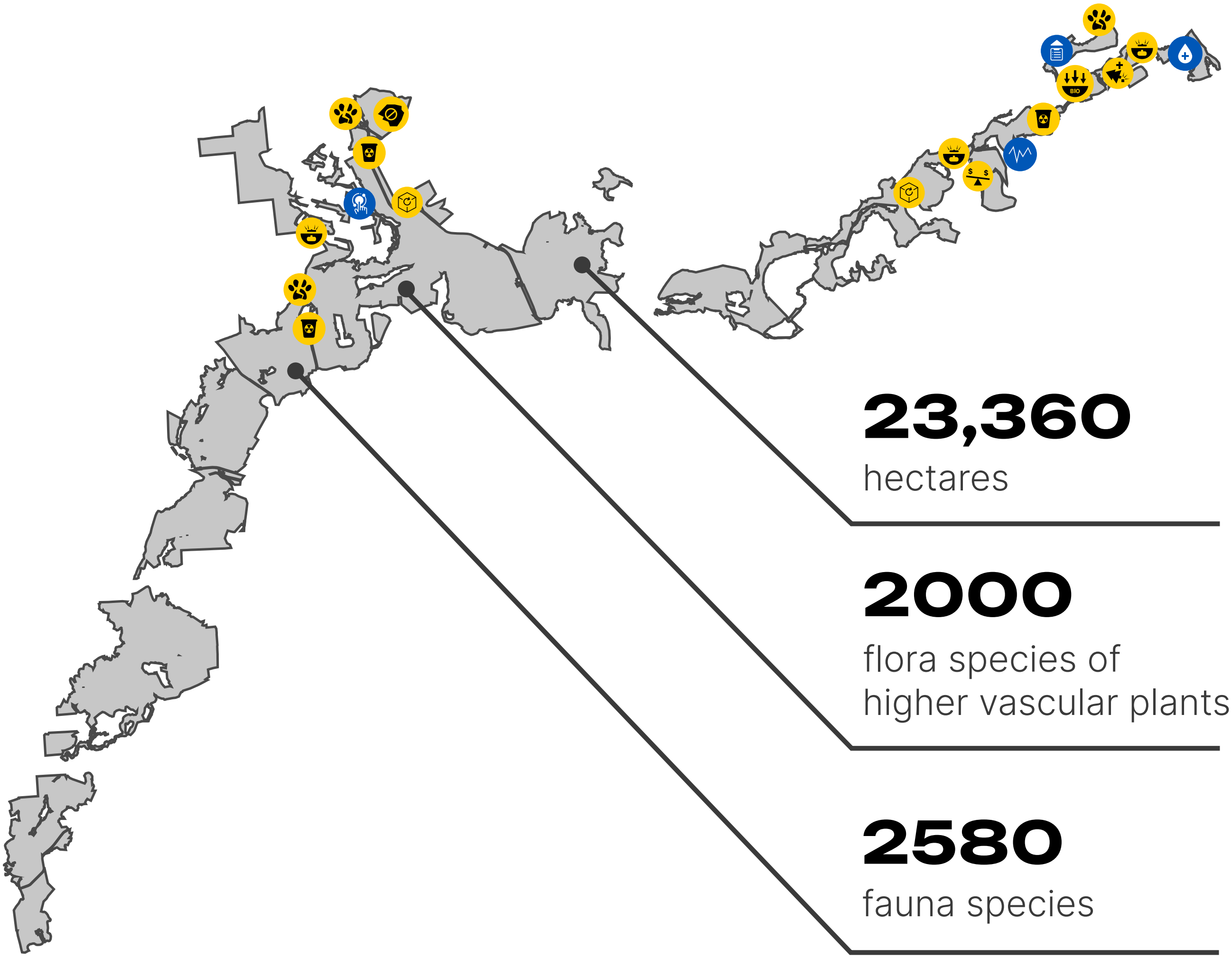

Figure 5. Hetmanskyi National Nature Park

ACTION PLAN:
BEFORE THE END OF MILITARY ACTIONS

- MONITORING AND RISK ASSESSMENT
- EMERGENCY STABILIZATION TREATMENTS
- DIGITALIZATION AND MAPPING OF THE PROCESSES OF MONITORING
- RESTORATION MEASURES PLANNING

ACTION PLAN:
AFTER THE END OF MILITARY ACTIONS

- DEMINING AND ENSURING THE SAFETY OF THE TERRITORY
- COLLECTING BIODIVERSITY DATA
- MILITARY WASTE REMOVAL
- HABITAT RESTORATION AND CONSERVATION
- MONITORING OF TERRITORIES THAT WERE INACCESSIBLE
- SUPPORT OF POPULATIONS OF ABORIGINAL, VALUABLE AND RARE SPECIES
- REGAINING OF FINANCIAL STABILITY
- MONITORING AND ASSESSMENT OF BIODIVERSITY DYNAMICS AFTER RESTORATION
- REBUILDING OF INFRASTRUCTURE
- DEVELOPING CRISIS RESPONSE PLANS FOR WILDLIFE
- DEVELOPMENT OF COMPLEX RESTORATION MEASURES
- CONDUCTING ENVIRONMENTAL PROTECTION AND EDUCATIONAL ACTIVITIES
- SOIL RESTORATION BASED ON SOIL ANALYSIS
- REHABILITATION FOR BROKEN CROWNS AND TREE FALLS

NATURE PROTECTED AREA:

NATURE PROTECTED AREA:

Has a total area of 10,988.14 ha. There are 23 endangered natural habitats.

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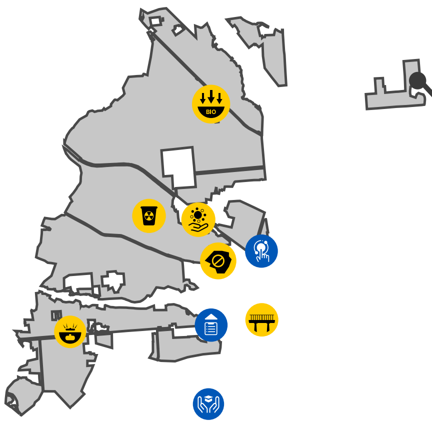
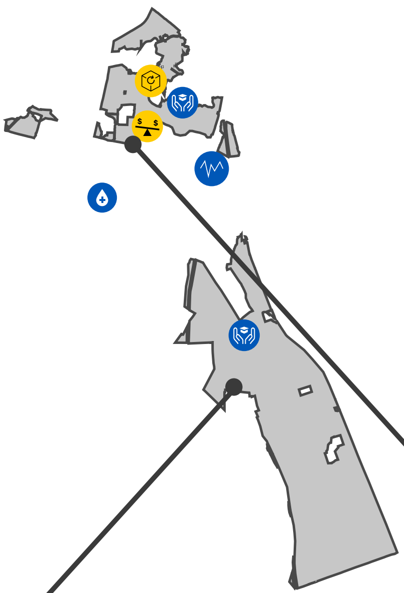
colortype of icon, which shows actions before the end of military actions



10,988.14 ha
of a total area



650
flora species of higher vascular plants,
118 species of bryophytes and more than **60** species of aphilophoroid fungi.

1230
total fauna species.
31 species of terrestrial molluscs,
190 species of insects and **181** species of vertebrates

Figure 6. Holosiivskyi National Nature Park

ACTION PLAN:
BEFORE THE END OF MILITARY ACTIONS

- MONITORING AND RISK ASSESSMENT
- DIGITALIZATION AND MAPPING OF THE PROCESSES OF MONITORING
- EMERGENCY STABILIZATION TREATMENTS
- FAST SOIL ANALYSIS AND MILITARY WASTE REMOVAL
- REHABILITATION FOR BROKEN CROWNS AND TREE FALLS
- CONDUCTING ENVIRONMENTAL PROTECTION AND EDUCATIONAL ACTIVITIES

ACTION PLAN:
AFTER THE END OF MILITARY ACTIONS

- DEMINING AND ENSURING THE SAFETY OF THE TERRITORY
- MILITARY WASTE REMOVAL
- MONITORING OF TERRITORIES THAT WERE INACCESSIBLE
- REGAINING OF FINANCIAL STABILITY
- REBUILDING OF INFRASTRUCTURE
- DEVELOPMENT OF COMPLEX RESTORATION MEASURES
- COLLECTING BIODIVERSITY DATA
- HABITAT RESTORATION AND CONSERVATION
- SUPPORT OF POPULATIONS OF ABORIGINAL, VALUABLE AND RARE SPECIES
- MONITORING AND ASSESSMENT OF BIODIVERSITY DYNAMICS AFTER RESTORATION
- DEVELOPING CRISIS RESPONSE PLANS FOR WILDLIFE

5. Conclusions

In the context of ongoing war, systemic scientific effort required for the environmental assessment of protected areas remains fragmented. This fragmentation arises due to several factors, including infrequent environmental assessments and sporadic programmatic actions for restoration, often constrained by limited funding. The lack of accountability for the impact on geosystem functioning caused by armed conflicts exacerbates this challenge, undermining global efforts to identify effective restoration strategies for areas affected by military activities.

During the Russian war against Ukraine, significant landscape disturbances were observed, leading to the degradation of soil, vegetation, and biodiversity. The Chornobyl REBR, the Holosiivskyi NNP, the Desniansko-Starohutskyi NNP, and the Hetmanskyi NNP have a strong need for material and non-material resources, including financing of nature conservation and research, provision of fuel and lubricants, and equipment for research. Due to the limited access (due to unexploded ordnance or mines), it is impossible to effectively control protected nature reserves and protect biodiversity (e.g. from fires, poaching, illegal logging, etc.).

The GIS analyses, on-site assessments, and soil sample analyses conducted in this white paper highlight the destruction of natural soil horizons and disruption of pedogenic sequences, altering numerous soil properties. The soil sample analyses found that the protected areas are contaminated with elements of hazard classes 1–3, such as lead, manganese, zinc, copper, vanadium, strontium, etc. In the military zones of the studied areas, regardless of soil type, accumulation of metals in the upper humus horizon was identified.

This white paper also reveals the collateral damage from military actions, including habitat destruction, disruption of ecosystems, release of hazardous substances, and damage to research infrastructure. These damages not only harm biodiversity but also compromise crucial environmental research, especially in post-war recovery of ecosystems. The QGIS analysis further demonstrates the significant impact on protected nature reserves, highlighting the urgent need for environmental restoration efforts.

Selecting a remediation technology requires careful consideration of various factors, including costs, technological readiness, environmental impact, and public opinion. In the scenarios of catastrophic contamination, such conservation measures as suspending land use and initiating reforestation become necessary. Granting these lands a conservation status facilitates natural restoration and conservation-oriented management.

A proposed system of measures includes consistent and constant monitoring of affected areas, prioritizing critical sites for immediate post-conflict intervention, and developing a „Marshall Plan for Environmental Reconstruction” to guide restoration efforts with national and international support.

Future studies could extend this research by monitoring environmental variables over the long term, employing qualitative analyses to understand the extent of environmental damage, and leveraging satellite imagery for comprehensive damage assessments. Understanding social implications of environmental degradation also warrants further research.

Moreover, given the wide variety of initiatives and efforts concerned with natural resources conservation and recovery during the war, it is suggested that a project be undertaken that can congregate information on different projects, connect various stakeholders, and act as a “hub” in the dissemination of events, publications, study reports, and funding opportunities to support current and on-going initiatives. The staff at the project Ukraine Nature will in the coming months engage in actions with the objective of setting up the “Ukraine Nature Network”, hence continuing the work initiated as part of this project.

Given the scarcity of data on post-war environmental restoration and nature conservation during the war, this white paper’s findings are invaluable, highlighting the urgent need for targeted restoration and preservation efforts in the face of ongoing military threats. The results should inform future management decisions, legislative initiatives, and international awareness regarding the environmental consequences of war. Additionally, the findings should be shared through scientific conferences, publications, and discussions with experts to foster a collaborative approach to „green recovery”.

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