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Research article

The environment as the first victim: The impacts of the war on the preservation areas in Ukraine

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ABSTRACT

The war in Ukraine has had a devastating impact on the environment. Military actions have caused the release of hazardous substances into the environment, such as pollutants and toxic chemicals, that have contaminated the water, soil, and air, posing a threat to both human health and the environment. This has resulted in widespread destruction and contamination of natural habitats and resources and has disrupted wildlife populations and ecosystems. The impacts of military activity on the soils of protected areas are particularly critical, as they are the basis of biotic and landscape diversity and require special management and scientifically based monitoring measures even in peaceful conditions. In this context, this communication paper aims to provide an overview of the impacts of the war on the soils in four Ukrainian protected areas, namely Chornobyl Radiation and Ecological Biosphere Reserve; Desniansko-Starohutskyi National Nature Park; Holosiivskyi National Nature Park, and Hetmanskyi National Nature Park. To address these aspects, this paper combined GIS analysis and secondary data including soil samples obtained during field expeditions, to provide evidence of how ground battles, occupation, terrestrial land mines, and explosions can severely impact the soils. Practical and theoretical implications of the military actions are also discussed.

1. Introduction

Similar to various other armed conflicts, the Russian war against Ukraine has had a devastating impact on the environment. What makes this war particular is the widespread destruction and contamination of natural habitats and resources, making the environment - apart from humans - one of the first victims. This is substantiated by the wide disruption of wildlife populations and ecosystems (Rawtani et al., 2022).

One of the major environmental impacts of the war has been the destruction of infrastructure and facilities, such as power plants, factories, and chemical storage facilities (Pereira et al., 2022a). This has resulted in the release of hazardous substances into the environment, such as pollutants and toxic chemicals, which have contaminated the water, soil, and air, posing a threat to both human health and the environment (Dmytruk et al., 2022; Pereira et al., 2022b).

Another impact of the war has been the destruction of wildlife habitats, such as forests and wetlands, which has disrupted the balance of ecosystems and led to the loss of many plant and animal species (Dmytruk et al., 2022; Wenning and Tomasi, 2022). The displacement of people due to the conflict has also significantly impacted the environment beyond the area of active ground hostilities (Cockbain and Sidebottom, 2022; Sasse, 2020).

In addition, the war has caused much deforestation, responsible for significantly destroying the country's forests. This has, in turn, led to a

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substantial decrease in the quality of wildlife habitats, a loss of soil fertility, and increased air pollution. In addition, soil erosion and land degradation are more present than ever before, leading to the loss of fertile land and reducing the ability of the land to support agriculture and forestry (Jagtap et al., 2022). Table 1 outlines some of these impacts.

The environmental impacts of wars usually extend beyond the immediate conflict zones, affecting neighboring regions and contributing to global environmental challenges. Addressing these impacts requires concerted efforts for environmental assessment, restoration, and protection as part of post-conflict recovery and peace-building processes.

In the context of permanent military conflicts with corresponding negative effects on the environment, systematic scientific developments in the field of the environmental assessment of protected areas are fragmented. This is because the environmental assessments of the territories have not always been carried out and published, and programmatic actions for environmental restoration have been carried out in rare cases with funding on a residual basis.

The lack of accountability for the consequences of impacts on geosystem functioning caused by armed conflicts and military activities undermines global efforts to choose appropriate ways to restore areas of military activity.

According to the Ministry of Environmental Protection and Natural Resources of Ukraine, since the beginning of the war, 812 protected areas with different types of military impact have been affected. In response to this crisis, authors concentrated its research efforts on four areas within the Kyiv and Sumy regions: the Chornobyl 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) (Fig. 1). These areas were selected based on information 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.

Table 1
Some of the impacts of the war on the environment.

War component	Environmental implications
Land degradation by traffic of tanks and artillery	Military operations, including the movement of heavy machinery, artillery bombardments, and troop movements, have led to significant land degradation. This includes the destruction of vegetation, soil compaction, and disturbance of land, which can lead to increased erosion and reduced soil fertility
Air and water pollution	Wars lead to considerable pollution due to the use of weapons, destruction of industrial sites, and burning of fossil fuels. This pollution includes the release of hazardous substances into the air, water, and soil, which can have detrimental effects on human health and ecosystems.
Use of military-grade materials	The conflict generates large amounts of military waste, rubble from destroyed buildings, and hazardous materials, posing significant challenges for waste management and increasing pollution risks.
Wildlife and habitats degradation	Wars often lead to the destruction of habitats and have a direct impact on wildlife. Noise, pollution, and physical destruction of habitats can disrupt wildlife populations and lead to declines or local extinctions.
Agricultural impacts	Wars often disrupt agricultural activities, leading to land abandonment, loss of crops, and reduced agricultural productivity. This not only affects local food supply but also has broader implications for global food security.
Forests and protected areas	Forests and protected areas are not immune to the impacts of war, suffering from direct damage due to military activities as well as increased vulnerability to illegal logging and poaching due to weakened governance and oversight.

Source: the authors.

Chornobyl REBR was officially established in 2016 - 30 years after the Chornobyl disaster. The reserve is unique and the largest in Ukraine, covering almost 227 thousand hectares. On its land, there is a large deal of diversity, including 120 species of lichens, 200 species of mosses, 303 species of vertebrates, and 1256 species of higher plants (Chornobyl, 2023). Holosiivskyi NNP is located in Kyiv, in its southern and western parts. It is the largest protected area in the city of Kyiv, with a total area of about 11,000 ha (Potapenko et al., 2020). There are 23 endangered natural habitats requiring specific conservation measures on its territory (Nature Reserve Fund of Ukraine, 2023a,b,c). Desniansko-Starohutskyi NNP is situated in the Sumy region in the far north of Ukraine and occupies 16,214 ha. Most habitats of the NPP are designated in the Red Book of Ukraine, and 25% of all vertebrate species included in the Red Book of Ukraine live in this area (Desniansko, 2023). Moreover, the Desna floodplain in the Ramsar site is located in the western part of the park. Hetmanskyi NNP is situated in the southeast of the Sumska oblast, and it borders with the Russian Federation in the east. There are over 1013 plants and 2580 animal species in this park, and many of these species are officially registered on the endangered list (Nature Reserve Fund of Ukraine, 2023a,b,c; Hetman National Nature Park, 2023).

The current state and ongoing changes in the landscape complexes of protected nature resevres as a result of hostilities require more attention and organisational measures. The lack of comprehensive research on the territories of protected areas affected by military impact leads to the transformation and sometimes complete degradation of unique areas. Sometimes their restoration after military intervention becomes impossible. In this way, individual biotic species and landscape complexes as a whole are gradually lost.

During our research, it was discovered that valuable habitats of these four protected areas were endangered by occupation and mine danger, fires caused by shelling, ground battles (armed clashes), remote violence (explosions, shelling), military vehicles and machinery relocation, as well as maintenance and repair. The main consequences of the impact of hostilities on the soils of protected areas are the physical, chemical and biological degradation of soils, the formation of zones of increased geochemical risk, the mining of territories, contamination with solid waste (remnants of ammunition, anti-personnel mines, explosives, damaged and abandoned military equipment), destruction or damage to recreational infrastructure, which leads to a deterioration of the ecosystem integrity due to the destruction of vegetation and deterioration of soil structure, and thermal impacts (occurrence and spread of forest fires), which lead to a reduction in biodiversity.

2. Methods

This paper aims foster a great understanding of the impacts of the Russian waron the environment, particularly the soils in Ukrainian preservation areas. To obtain the results, the authors relied on GIS analyses as well secondary data gathered by experts from the Ukraine Nature Project in two stages: during the expedition (Splodytel et al., 2023) and extracted from data bases (ACLED, FIRMS, Ministry of Defence of Ukraine and State Emergency Service of Ukraine).

2.1. Researched areas military actions

Based on the information on war incidents from ACLED (Armed Conflict Location & Event Data Project, 2023), and given the moderate spatial accuracy of the incidents' geographical locations, the density of the incidents was calculated. For this, a neighborhood of a 3 km radius was selected for density calculation with raster output of 250 m spatial resolution.

The number of fires recorded within four studied protected nature reserves was assessed based on the extracted data from Fire Information

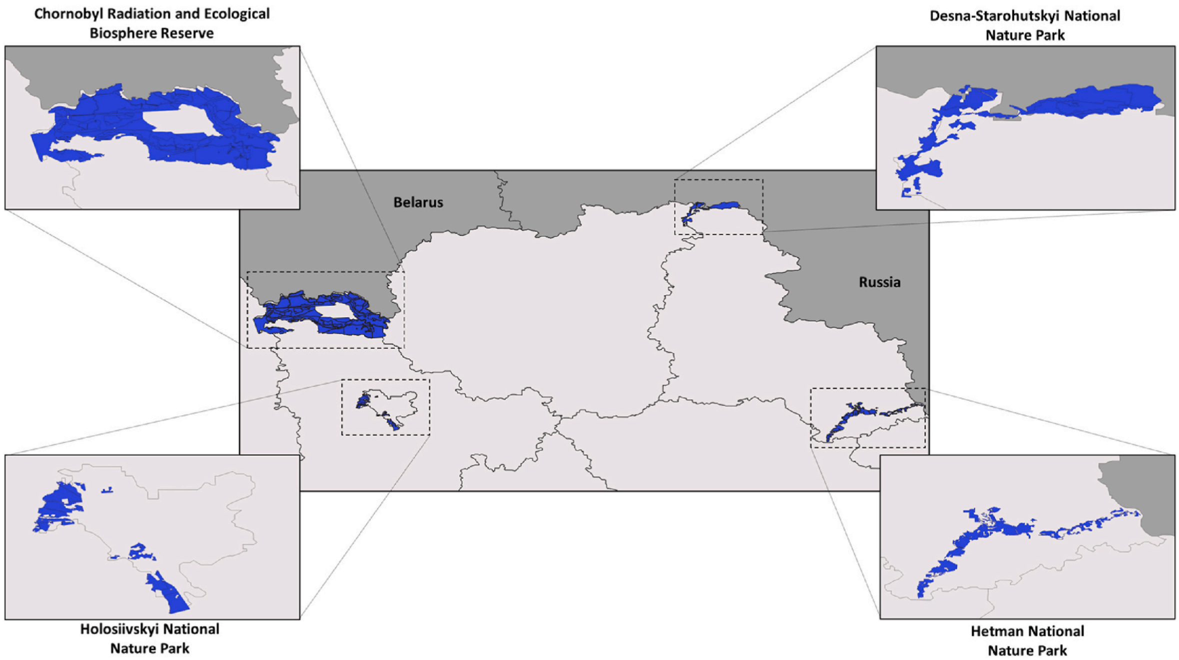

Fig. 1. Selected Ukrainian protected nature reserves.

for Resource Management System (FIRMS). Information from the Visible Infrared Imaging Radiometer Suite (VIIRS) was employed with spatial resolution 375 m, which allows detection of the smaller fire events, in comparison to other similar instruments for fire monitoring. Each record in the accessed database represents the centre of the appropriate 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 neighboring pixels and time sequence. To identify the extent of burnt area within four studied ares the following steps have been done. 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, infrared) complemented by an NDVI band computed for the same dates as the analyzed images. The classification employed a Random Forest (Ho, 1995.) algorithm for which training polygons were manually delineated based on freely available high-resolution imagery from Google Earth or the same images that undergo classification. Since the acquisition dates of processed images for each protected nature reserves were different, the classification procedure was run separately for each researched area.

The risk of mine and/or UXO (Unexploded Ordnance) contamination in researched protected nature reserves was assessed using the official geo-portal of the State Emergency Service of Ukraine (https://mine.dsns.gov.ua/) as of November 1, 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.

In the third stage of our study, information extracted from databases and satellite images was processed by QGIS software(http://qgis.org).

2.2. Estimation of impacts on soils

Soil sampling was conducted in October 2022. 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. Soil sampling and analyses in the study areas was also carried out in 2017–2018 to determine the natural geochemical background in the territories of the nature reserve fund. The availability of such a database made it possible to establish the levels of military impact in the study area with a qualitative separation of various anthropogenic impacts.

All samples were collected from depths of 0–5, 5–15 cm. The purpose of sampling at a depth of 5–15 cm was to assess the 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 use of the areas prior to the outbreak of hostilities and an examination of the weapons used were taken into account 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: to relate the results with the dry weight of the sample; 2) Separation of soil and organic fraction: to perform the analysis of soil samples without fractions of plant origin; 3) Grinding: to homogenise samples before the extraction; 4) Digestion: 0,3 g of each soil sample with,"reversed aqua regia'' (4,5 ml of 69% HNO_3 and 1,5 ml of 36% HCl) by using the microwave digestion system – 240 °C for 1h; 5) Dilution: up to 50 ml after transfer of each sample into the glass volumetric flasks; 6) Centrifugation to collect the supernatant solution; 7) Analysis.

At the third stage, the heavy metal content was measured. The content of heavy metals was determined by 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 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 natural soil. One of the most important elements of processing lithochemical information in geo-environmental studies was the reliable determination of background concentrations of chemical elements in soils. This is due to the fact that, at present, MPCs for the content of heavy metals in the soil cover are developed according to the hygienic approach, and the calculation of the total pollution indicator, which comprehensively characterises the degree of soil contamination, is based on the ratio of the recorded pollutant content to its background value.

2.3. c. bibliometric analysis

Finally, the investigation into the practises to resolve impacts of soil caused by the military actions was performed using the EOSviewer software (EOSviewer, 2021). The co-occurrence of terms technique was selected to explore the research streams that researchers have been discussing on soil restoring methods and techniques in the context of war. The results are presented in Table 3. "Examples of measures to address the impacts of military actions to soil".

3. Results and discussion

3.1. Military actions in the Ukrainian protected nature reserves

The natural landscape in Ukraine, particularly in the Emerald Network of protected nature reserves, is changing as a result of the war with Russia. It has made it difficult to maintain and protect these areas and has put additional pressure on ecosystems that are already threatened by human activities. In this regard, the Ukrainian government and the international community need to prioritise environmental protection in the country, even during the war, since issues related to the it - such as attacks, fires, presence of land mines, battlefields, and occupied territories - can put the natural ecosystems in danger and generate soil, water, and air pollution. However, information on the transformation of the landscape and, in some locations, the 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 and actual conservation activities. To tackle this challenge the authors discovered military drivers that lead to soil pollution and degradation (Broomandi et al., 2020). within the Chornobyl REBR, the Desniansko-Starohutskyi NNP, the Holosiivskyi NNP, and the Hetmanskyi NNP.

The occurrence of war-related incidents was assessed based on data available from ACLED for the period from 24th February to November 11, 2022. Geographical locations of the incidents are reported with an accuracy of several kilometres, attributing each incident to one place within a settlement or area based on information from primary sources (media, official reports etc.). Ground battles (armed clashes) and remote violence (explosions) incidents were recorded in ACLED database (ACLED, 2023). Four of the incidents are attributed to the territory of Chornobyl REBR and represent the armed clashes that happened on 4–15th March 2022. The other 13 incidents were reported within Desniansko-Starohutskyi NNP, namely Znob-Novhorodska hromada, in the form of explosions from shelling, artillery or missile attacks from 16th July to November 9, 2022.

Fig. 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. The data used to create the figures were obtained by the project Ukraine Nature (https://www.haw-hamburg.de/en/research/research-projects/project/project/show/ukraine-nature/), which is coordinated and managed by the authors of this paper.

Chornobyl REBR and Hetmanskyi NNP were the territories that the Russian military forces occupied. Among the four researched protected nature reserves, three are potentially dominated by land mines, whereby Chornobyl and Desniansko-Starohutskyi are expected to have almost the total area endangered by land mines, and Hetmanskyi NNP has a small portion located in the northeast part of the nature park.

Regarding burnt areas, the red polygon in Fig. 2 indicates that Chornobylskyi REBR presented part of its territory damaged by fires,

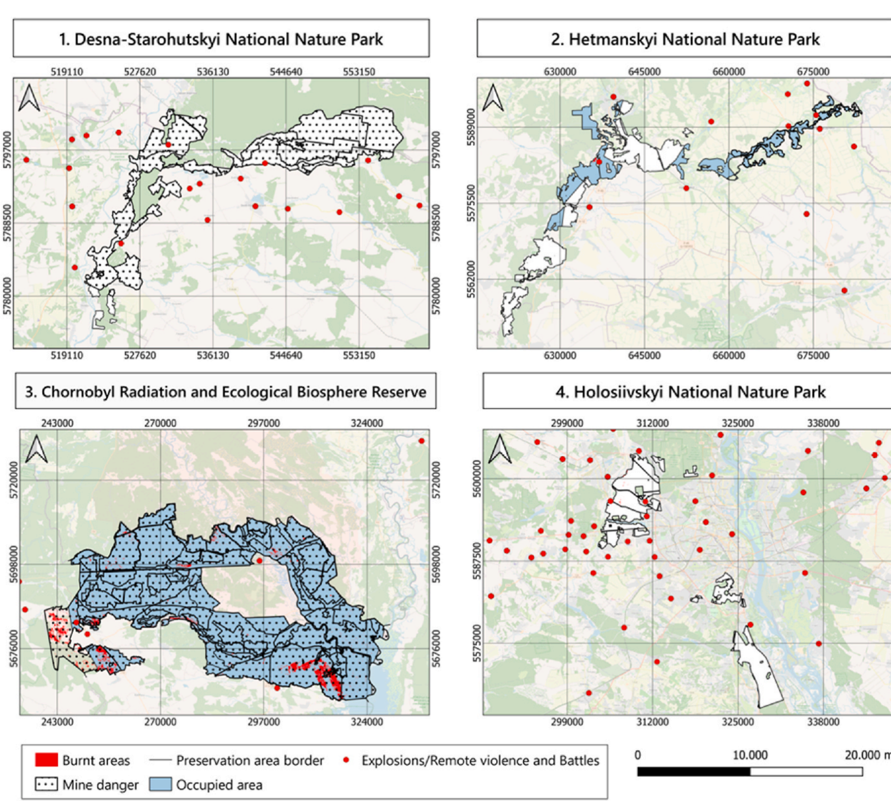

Fig. 2. Distribution of military actions recorded in the studied areas.

especially in the west and southeast. These aspects are understood as a result of the several explosions, remote violence, and battles expressed by the red dots noticed in all four researched protected nature reserves. During the occupation of the Chornobyl REBR (in the period from February 24, 2022 to May 1), 2022, fires caused by the occupiers damaged soil cover on the area of 31,760 ha out of 227 thousand hectares. Therefore, according to our results and confirmed with the Chornobylskyi REBR database almost 14% of its territory was burned during the occupation.

The number of fires recorded within the four studied protected nature reserves was assessed based on remotely sensed data, extracted from the Fire Information for Resource Management System (FIRMS) (Fire Information,) for the period from 1st January to November 1, 2022. To reveal both the direct and indirect impact of the hostilities on fire patterns since the conflict escalation in 2022, several indicators were calculated and compared to the mean values of the reference period, which is defined as the previous 5 years (2017–2021). These are: (1) the total number of fires in 2022 and (2) its monthly number in comparison with the average values for 2017–2021; and (3) the annual fire density statistics across the protected nature reserves for 2022 versus the average values in 2017–2021.

The total number of recorded fires for 10 months of the year in 2022 was 1757 in Chornobyl REBR. This was four times higher than the 5-year average number and constitutes 80% of the total number for this period. The most striking hot spot fire density reached its maximum of 13 fire events per 1 square kilometre. Moreover, three less pronounced hot spots emerged not far from the abandoned Chornobyl town where an emergency service unit exists and where fires were not recorded before. But when considering only the period of ground occupation of Chornobylskyi REBR between 24th of February and the beginning of April 2022, the total number of fires was 290, which is only 16.5% of the total number in 2022. Accessibility of the conflict-affected area, which includes the entire Chornobylskyi REBR, for extinguishing fire is limited if not impossible and is due to mine and unexploded ordnance contamination. There is evidence of incidents with fire brigades during and after the occupation linked to mine explosions, including Chornobyl REBR. Therefore, we attributed all the fires that occurred after full-scale invasion to a direct or indirect implication of the warfare on the natural environment. In 2022, fires were recorded within Hetmanskyi and Holosiivskyi NNPs only in March, while normally they happen in the spring and autumn seasons. Interestingly, in Hetmanskyi NNP the number of fires in March 2022 was 2/3 of the 5-year average, but in Holosiivskyi NNP the number was 10 times higher than usual.

The only burning site within the Hetmanskiy NNP was discovered south of the village Sosonka (Sumy region), which is part of a regulated recreation area. Its area is estimated at 24.3ha and belongs to the floodplain grasslands of the Vorskla River. The burned area appeared between 23rd and March 26, 2022, and it is the only burned area detected in 2022 using Sentinel-2 imagery.

According to the database of the Ministry of Defence of Ukraine, two out of four protected nature reserves experienced direct occupation by the Russian Armed Forces since full-scale invasion began on February 24, 2022. Chornobylskyi REBR and Hetmanskyi NNP were out of the area under governmental control between 24th February and the beginning of April 2022, thus totalling about 1.5 months. Most of the impacted area belongs to Chornobylskyi BR, about 94% (or 213,000 ha) of which was under occupation. In addition, about 46.3% (~11,000 ha) of Hetmanskyi NNP was under occupation.

After regaining governmental control under these areas, the risk of mine and/or UXO (Unexploded Ordnance) contamination and leakages of fuel or harmful chemical substances is particularly high. It may be quantified by estimating the extent and duration of occupation within PAs and the number of damaged military vehicles, machinery, and mined areas. The last source of risk was assessed using the official geoportal of the State Emergency, 2023; Splodytel et al., 2023. There are two categories of land in terms of mine contamination that are distinguished on the official geo-portal: potentially mine contaminated (PMC) and confirmed mine contaminated (CMC).

Chornobylskyi REBR, with the exception of only 12 ha that is marked as CMC, is classified as PMC. Almost the entire area of Desniansko-Starohutskyi NNP (about 98%) and only 15% of Hetmanskyi NNP fall within the PMC zone, which stretches along the state border with the Russian Federation. In addition, a small area of 12 ha within Hetmanskyi NNP is defined as CMC according to official data. Within Holosiivkyi NNP, only 0.3% of entire territory (equal to 34 ha) is PMC, which is the lowest level among all project PAs.

All the described military actions due to Russian Federation's military offensive (occupation, mine danger, fires caused by shelling, ground battles (armed clashes), remote violence (explosions, shelling)), could lead to anthropogenic changes to soil features based on 160 previous study results covering disturbances during military training and warfare analyzed by (Broomandi et al., 2020). Information extracted from databases and satellite images became a basis and proceeded by field expeditions and soil sample analyses for the comprehensive research documenting physical/chemical disturbances in soils following military activities in researched areas.

3.2. Impacts on soil on the researched areas due to military actions

Authors relied on secondary data presented in 3.1. as well as gathered by experts from the Ukraine Nature Project, who travelled to the parks to conduct a field expedition with preservation areas representatives and the security service to collect soil and water samples and examine territories in order to evaluate environmental damages, particularly to the soil. Results are presented in Table 2.

Along with the mining of the territory with explosive objects, in the Holosiivskyi NNP the mechanical impacts are also typical, which consists of the mechanical deformation of the ground cover due to the construction of defence infrastructure (surface and underground structures). As a result of the violation of the genetic horizons of the soil cover, the adaptation of plants to climate changes, arid conditions and lack of moisture worsens. This intensifies a number of dangerous geomorphological processes: landslides, soil subsidence, etc. In the territories of military operations, a violation of the homogeneity of the soil is recorded at a depth of up to 1.5 m.

In the burned areas in Chornobylskyi REBR, there is a removal of humic substances and the formation of a hydrophobic layer, which limits the infiltration of water. According to the Chornobylskyi REBR database, the soil and vegetation cover was damaged in an area of 31,760 ha due to fires during the Russian occupation. A change in acid-alkaline conditions towards a neutral pH reaction is quite expected for the soils of the territories affected by fires, which is explained by the penetration of ash water-soluble compounds into the soil profile and the saturation of the absorbing complex with alkaline earth elements, which causes a shift in the reaction of the environment. Mechanical disturbance of the soil cover (trenches, dugouts, etc.) makes up about 6% of the territory of the reserve and does not pose significant threats to the landscape of the territory.

For the Desniansko-Starohutskyi NNP, the most typical damage is mechanical and chemical contamination of the ground cover caused by constant shelling, artillery, or missile attacks (projectile weight 21.76 kg–43.56 kg), which leads to the formation of craters. The explosive wave provokes the destruction of the sequence of soil horizons with an obvious violation of the air-water regime. The soil remaining at the impact site is turbulent, subjected to dynamic compaction, and also contains numerous metal debris with remnants of explosive toxic substances.

For the Hetmanskyi NNP, in addition to the overlaying of occupation zones on the top of the territory of mining, the formation of so-called manufactured deepening in the form of funnels from ammunition explosions and the formation of depressions and bulk landforms as a result of fortification works are very common. It is also worth noting the

Table 2
Damages on soil on the researched areas due to military actions.

	Military actions	Impacts on soil	Data source
1	Holosiivskyi National Nature Park		
	• Construction of defence infrastructure (surface and underground structures) • Direct artillery fire by using high explosive fragmentation and cumulative shells weighing from 6.5 to 43.56 kg.	Mechanical damage to soil and vegetation (including trees) due to construction of defence infrastructure Worsening of adaptation of plants to climate changes, arid conditions and lack of moisture Intensification of dangerous geomorphological processes: landslides, soil subsidence, etc. Violation of the homogeneity of the soil is recorded at a depth of up to 1.5 m.	Field expedition
2	Chornobyl radiation and ecological biosphere reserve		
	• Occupation by Russian Armed Forces (94% of the territory) • Ground battles (armed clashes) • Occurrence of fires due to the use of weapons systems. Burned area during occupation 14% of the territory • Detonation of explosive objects • Construction of defence infrastructure (trenches, dugouts, etc.) makes up about 6% of the territory • Potentially mine contaminated (almost entire territory)	Removal of humic substances and the formation of a hydrophobic layer, which limits the infiltration of water. A change in acid-alkaline conditions towards a neutral pH Soil and vegetation cover was damaged in an area of 14% of the territory because of fires during occupation	Ministry of Defence of Ukraine FIRMS Sentinel-2 Chornobyl REBR ACLED State Emergency Service of Ukraine
	Desniansko-Starohutskyi National Nature Park		
3	• Potentially mine contaminated (98% of entire territory) • Shelling, artillery or missile attacks by using high explosive fragmentation and cumulative shells weighing from 21.76 kg to 43.56 kg	Formation of craters, mechanical and chemical pollution, soil, and vegetation damages by constant shelling Destruction of the sequence of soil horizons with an obvious violation of the air-water regime Soil remaining at the impact site is turbulent, subjected to dynamic compaction, and contains numerous metal debris with remnants of explosive toxic substances.	State Emergency Service of Ukraine ACLED, field expedition
	Hetmanskyi National Nature Park		
4	• Shelling, artillery or missile attacks • Movement of tracked and wheeled military equipment • Spilling over of lubricants, used oils, antifreeze, and organic solvents on the military equipment maintenance and repair areas • Significant spills of petroleum products in field petrol filling stations • Occupation by Russian Armed Forces • Construction of defence infrastructure (surface and underground structures) • Potentially mine contaminated (15% of the territory)	Funnels from ammunition explosions Depressions and bulk landforms due to construction of defence infrastructure Significant disturbance of the soil and vegetation cover Destruction of the upper fertile layer of the soil cover Overwetting of the terrain Maintenance and repair areas of military equipment are contaminated with fuel and lubricants, used oils, antifreeze, and organic solvents. Disappearing ability of self-recovery and the complete destruction of microorganisms due to changes in the chemical composition of the soil	Field expedition Ministry of Defence of Ukraine State Emergency Service of Ukraine

significant disturbance of the soil and vegetation cover in different places as a result of the use of weapons and the movement of military equipment. Such belligerative disturbances are the most visible on dry sod-podzolic sandy soils of the levelled terrace. The movement of tracked and wheeled military equipment on the territory of NNP leads to destruction of the upper fertile layer of the soil cover. Moreover, tracks and multi-track paths of considerable depth are formed on the routes of military equipment, which are often filled with water, causing overwetting of the terrain. Due to maintenance and repair of military equipment in fields in the territory of Hermanskyi NPP, the area is contaminated with fuel and lubricants, used oils, antifreeze, and organic solvents. Most often, at the sites of significant spills of petroleum products in field petrol filling stations in the preservation areas, an important property of the soil - the ability to self-recovery – disappears, and the complete destruction of microorganisms occurs, due to the changes in the chemical composition of the soil.

Our research results confirm analyses by (Broomandi et al., 2020) that soil found in hollows/funnels made by explosions is compacted, perturbed, and contaminated by metallic fragments. As well as the statement that fire-induced damages and military traffic also making soils more vulnerable to erosion and runoff. However, according to our field expedition, the main negative impact of military traffic on soil is not only compaction but also damage to vegetation and the destruction of the upper fertile layer of the soil cover.

3.3. Soil sample analyses

During the field expedition in October 2022, 63 samples were collected from the combat damage zones and 20 background samples from the study areas.

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 study identified areas with an increased content of chemical elements that form point military-technogenic geochemical anomalies. 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 study areas of Hetmanskyi NNP, Desniansko-Starohutskyi NNP and Holosiivskyi NNP national nature parks are characterised by the effects of direct-fire artillery firing using high-explosive and fragmentation shells with a weight of 6.5–43.56 kg.

All types of ammunition used in combat operations (high-explosive, fragmentation, armour-piercing, cumulative shells and mines) are characterised 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 s. 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.

The most contrasting elements of military-technogenic origin in the study area are 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 is as follows: Zn > Pb > V > Mn > Cu.

The soils of Holosiivskyi NPP are characterised by the lowest content of 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 values.

In the areas of bombardment of Hetman National Park, 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. The copper content exceeds the background by 2 times in the areas of air bombardment. For the areas of artillery shelling, the copper content was recorded within the background values. In some samples, the cadmium content is close to the MPC (0.5 mg/kg) but does not exceed it.

For Desniansko-Starohutske NPP, the zinc exceedance by 1.4 times is typical for 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 exceeds the background by 13 times and the MPC by 6.4 times. The lead content exceeds 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.

For the Chornobyl Radiation and Ecological Biosphere Reserve, the concentrations of gross forms of all the 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. In contrast to the background samples, the presence of lead and zinc was detected in the range of 8–12 mg/kg.

As a result of pyrogenic impact, the physical and chemical properties of the soil cover have changed. Reducing the content of water-soluble compounds and neutralising the pH contribute to the mineralisation of organic matter and differentiation of the soil profile under conditions of increased exposure to anthropogenic metals. An increase in the calcium content by 4.3 times and a decrease in magnesium by 2 times were detected.

According to the additional results of the ICP analysis with inductively coupled plasma, in soil samples from the burned area (Kupovate village), the concentrations of gross forms of all studied anthropogenic metals are several times higher than in the background soil (Table 2).

For the military zones of the studied protected nature reserves, regardless of soil type, there is a clear accumulation of metals in the upper humus horizon. This is primarily due to the aero technogenic nature of pollution and the ability of sorption with mineral and organic soil components to form stable compounds. The concentration of chemical elements in the soil samples does not exceed 0.3–0.5 times the regional background content on average.

The soils of the protected nature reserves can be considered as slightly contaminated with heavy metals, except for point military-technogenic anomalies. Due to low resistance to pollution and high migration sensitivity of soils, the threat of groundwater contamination is growing. According to our results contamination distribution depends not only on firing activity, soil properties, soil exposure time, and climate (Broomandi et al., 2020), but also on the type of weapon and the weight of the explosive part. It should be noticed that concentrations of certain chemicals and heavy metals in the damaged sites are a result of the volume of hazardous materials released by explosions and bombings. These impacts are local and soil contamination is often limited to the landing points of bombings and surrounding areas. This increases the risks of leachings, which may spread the contaminants more broadly. We agree with (Broomandi et al., 2023) that more studies are needed to cover a range of chemical warfare agents (CWAs) due to the significant scarcity of information about the impact of CWAs on soil ecosystems and their potential risk to human health and biota. At the same time, we can confirm difficulties of access to collect naturally contaminated samples and challenges in determining the contaminants, especially with their distribution in the soil and not only due to limited access to the side but also to the financial issues of such type of research.

3.4. Measures for soil damages mitigation

The potential long-range impact on soil depends on multiple factors (climate, geographical zone, duration of war, type of soil, type of impacts etc). In the Southern Caucasus, Bosnia, or Croatia, much of the areas still suffer from substantial landmine contamination (Baumann and Kuemmerle, 2016).

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 of erosion in steep areas, mainly as a result of forest fires fires (Almohamad, 2020). In the Sabab AI-Ahmad Nature Reserve of Kuwait, even 10 years after severe damage caused by military activities, soil natural recovery did not result in the full restoration of land to their pre-disturbance levels, even though the researched reserve was protected from human activities during the post-liberation period and cleared of mines and ammunitions (Omar et al., 2005). The findings by (Broomandi et al., 2017), showed the possible correlation between the degree of anthropogenic soil pollutants, and the remains of Iraq-Iran war after 25years.

The effects of armed conflict on land systems over longer time periods remain under-researched and require interdisciplinary research efforts, bringing together geography, environmental sciences, political sciences, and anthropology (Baumann and Kuemmerle, 2016).

Based on previous experiences, we would recommend measures such as.

1) Monitoring soil loss dynamics can encourage decision-makers and planners to take appropriate soil conservation priority actions, thereby reducing land loss and degradation issues (Almohamad, 2020).
2) An active restoration programme is needed to restore the soil, as far as natural recovery may not result in full restoration (Omar,et al., 2005).

The choice of restoration measures requires a comprehensive consideration of a set of various factors. The principal aspects are the potential opportunities of technology to reduce the damage, costs to carry out the process, availability, and readiness to use technology, impact on the environment, duration of the process, and public opinion (Splodytel et al., 2023).

Among the broad range of available methods and techniques, we selected the most suitable for our researched areas when considering mapped military actions and discovered damage. Analyses was performed by using the VOSviewer software, taking into account 458 peer-reviewed documents. The bibliometric analyses results are represented in Table 3.

Soil erosion caused by fire is the most obvious environmental disturbance, because by reducing or eliminating the vegetation and ground cover, fires make the soil more susceptible to raindrop impact, reducing aggregate stability and promoting sediment detachment (Vieira et al., 2018). There are some emergency stabilization treatments such as mulching and seeding 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 (Depountis et al., 2020; Vetrita & Cochrane, 2019a,b; Syaufina, 2018) in order to find the right methods for soil remediation.

Bioremediation as an economical and environmentally friendly approach is based on microorganisms' capabilities to degrade toxins. This method aims at biostimulation and bioaugmentation of the natural attenuation of the contaminants with indigenous microorganisms (Baniasadi and Mousavi, 2018). Novel approaches for bioremediation including addition of novel materials, using GEMs, and integration of electrochemical strategies with biological methods could be very effective for remediation damaged area.

Recently it has been comprehensively studied the phytoremediation of the main heavy metals, namely arsenic, lead, cadmium, nickel,

Table 3
Examples of measures to address the impacts of military actions to soil.

Main Impacts	Methods and Techniques	Advantages and Disadvantages
Land mines: lead to soil contamination and put the lives of human beings and animals in danger.	• Demining/mining clearance: excavators, flails • Mine defusal	**Advantages** • Responsible mining clearance conducted by experts and military personnel can protect the population and preserve the 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 loss of nutrients, mineral composition and soil biodiversity.	• Military waste removal by specialised organisations and military personnel. • Soil detoxification • Biological treatment/bioremediation • Chemical treatments • Physical treatments	**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 the soil biodiversity. **Disadvantages** • Soil detoxification could be expensive and take some time to fix the problem, according to the type of contamination. • Bioremediation: additional detoxification approaches may be needed due to increased toxicity after partial biological processing • Physical treatments: high investments, destruction of soil structure, risk of secondary pollution, risk of destruction of nutrients and disturbance of soil properties • Chemical treatments: the residues of chemical treatment have a greater 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: aerator; gypsum (clay); introducing organic matter. • Trenches and damage caused by bombing: cover • Erosion: replant 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

mercury, iron, copper, and zinc using 24 species of trees, 33 species of plants, 20 species of flowers (Pouresmaieli et al., 2022). The results are very promising and can help environmental officials and governments to find a sustainable solution to get rid of heavy metals hazardous on ecosystem. For example, it has been shown that some plant species, like *Platanus orientalis, Robinia pseudoacacia and Fraxinus rotundifolia* are capable of accumulating substantial amounts of heavy metals in their tissues (Pietrzykowski et al., 2014; Pająk et al., 2017).

With regard to Chornobyl REBR, Desniansko-Starohutskyi NNP and Hetmanskyi NNP, all the restoration efforts should start with mining clearance, as far as most of its territories contain land mines, which limit not only assessment processes on-site but also the implementation of any other methods or techniques. Access to the territories is crucial in order to develop a system of measures for soil cleaning. At the same time, impact identification requires proactivity and commitment from several stakeholders 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.

4. Conclusions

The GIS analyses, on-site assessment and analysis of soil samples carried out in this study provided evidence of the destruction of established natural soil horizons, disruption of the natural pedogenic sequence, and alteration of a number of their properties. Taking into account these results on soil and landscape geochemical conditions, it is necessary to develop a national strategy for soil restoration in post-war areas that would also influence the entire network.

The initial step is to develop a system of measures for demining and cleaning the soil cover. For further development of relevant soil restoration programmes or plans, it is important to conduct a rapid assessment of the effects of hostilities (degree of damage, levels of contamination) based on an effective environmental monitoring system.

The choice of remediation technology requires the consideration of a number of different factors: costs of the process; availability and readiness of the technology; environmental impact; duration of the process; public opinion; and assessment of the scale and cost (Splodytel et al., 2023).

In the case of catastrophic levels of soil contamination, conservation is advisable. This involves suspending or restricting the economic use of land for a specified period of time. First of all, this means exclusion from agricultural use and reforestation and reclamation measures.

In this case, restoration takes place naturally. An additional tool to support such lands is to grant them a nature conservation status to allow for a conservation type of management.

The results indicate that apart from the war causing unprecedented harm to the population and human rights in Ukraine, the military actions also have caused collateral damage related to the destruction and contamination of natural habitats and resources, disrupting wildlife populations and ecosystems. In addition, the results shed light on the release of hazardous substances into the environment and the destruction of research infrastructure and facilities, which could compromise important research in the area, especially related to recovering the environmental systems after the war. Finally, the QGIS analysis demonstrated the extent of the impact on the natural parks studied, considering battles, explosions, and the presence of land mines.

This commentary also contributes to the literature, as it explores the environmental impacts of the war in Ukraine and the interconnections of human activities, armed conflict and environmental degradation. In this sense, an important theoretical implication would be the need to provide some priorities in the next stages of tackling the damages the war caused on water, soil and biodiversity. Finally, the results of this paper also show the importance of more map analysis (i.e., QGIS) to explore the environmental impacts of war in Ukraine and other places, evidencing the applicability of spatial tools and technology in dealing with sustainability challenges.

A system of measures to mitigate damages may include.

a) a better and constant monitoring of the areas bombed and shelled, so their environmental impacts may be documented and estimated more systematically, which will be helpful in future reconstruction and conservation efforts
b) a list of priority sites (e.g., watersheds) which will receive immediate attention once the hostilities end

Moreover, the authors suggest that a “Marshall Plan for Environmental Reconstruction” be prepared to guide future restoration efforts, mobilising national and international funding.

This study also brings ideas for future studies. Firstly, according to the results, other studies could continue monitoring the variables in this study through a long-term perspective. Secondly, a qualitative analysis could be deployed to understand in depth the extent of environmental damage caused by the war. Thirdly, the authors believe that more attention should be given to satellite imagery data, as it could bring relevant visual and statistical information about the extension of the damaged areas. With the war dragging on, more damages are to be expected for the natural environments and ecosystems. Finally, more research should be conducted to understand the connections between the social problems caused by environmental degradation.

Code availability statement

No custom code was used to generate or process the data described in the manuscript.

CRediT authorship contribution statement

Walter Leal Filho: Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mariia Fedoruk:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Formal analysis, Data curation. **João Henrique Paulino Pires Eustachio:** Formal analysis, Project administration, Software, Visualization, Writing – review & editing. **Anastasiia Splodytel:** Data curation, Formal analysis, Investigation, Methodology, Resources, Validation. **Anatoliy Smaliychuk:** Visualization, Validation, Software, Data curation, Formal analysis, Investigation, Methodology, Resources. **Małgorzata Iwona Szynkowska-Jóźwik:** Validation, Resources, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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