frontiers
in Environmental Science

TYPE Original Research
PUBLISHED 01 July 2026
DOI 10.3389/fenvs.2026.1823887

OPEN ACCESS

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RECEIVED 05 March 2026
REVISED 28 May 2026
ACCEPTED 29 May 2026
PUBLISHED 01 July 2026

CITATION
Leal Filho W, Fedoruk M, Kunyk O, Semak U, Yaroshenko N, Ruda M, Eustachio JPP, Dinis MAP and Luetz JM (2026) Ecocide in Ukraine: an assessment of geospatial and environmental evidence of war-related ecosystem destruction in Ukraine.
Front. Environ. Sci. 14:1823887.
doi: 10.3389/fenvs.2026.1823887

Ecocide in Ukraine: an assessment of geospatial and environmental evidence of war-related ecosystem destruction in Ukraine

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The ongoing war in Ukraine has triggered large-scale and multi-dimensional environmental degradation affecting soils, freshwater systems, forests, agricultural landscapes, atmospheric quality, and biodiversity. Beyond immediate physical destruction, these impacts compromise ecosystem resilience, human health, food security, and long-term environmental governance. Despite extensive monitoring efforts, there remains a lack of integrated and spatially explicit analytical frameworks that systematically link observable environmental damage to discussions surrounding the concept of ecocide and post-conflict recovery planning. This study provides a comprehensive and evidence-based assessment of war-related environmental degradation across Ukraine using a mixed-methods approach combining multi-temporal geospatial analysis of satellite imagery (including Sentinel-1/2, Copernicus Emergency Management Service, NASA FIRMS, and Global Forest Watch) with a structured qualitative synthesis of governmental, intergovernmental, and civil-society reports. The approach enables the identification, classification, and spatial quantification of observable environmental disturbances across key domains, including industrial infrastructure, hydrological systems, agricultural land, forest ecosystems, protected areas, and urban environments. The results reveal widespread land-cover transformation, soil degradation and potential contamination, disruption of hydrological regimes following critical infrastructure damage, intensified wildfire activity in conflict zones, significant forest loss, and transboundary atmospheric pollution. The study develops a geospatial typology of war-induced environmental impacts and examines how these patterns may be interpreted in relation to the proposed criteria of "severe, widespread, and long-term" environmental harm associated with contemporary ecocide debates. By integrating spatial indicators of conflict-related environmental disturbance with qualitative environmental evidence, this research advances methodological tools for environmental monitoring in conflict settings and supports risk-based zoning, prioritisation of ecological restoration, and the integration of scientific evidence into environmental governance and post-conflict environmental assessment, providing a scalable and replicable framework for analysing ecosystem degradation in war-affected regions.

KEYWORDS

conflict-related environmental damage, ecocide, ecosystem disturbance, environmental monitoring, geospatial analysis, post-conflict environmental assessment, remote sensing, soil and water contamination

1 Introduction

The war in Ukraine has become both a humanitarian crisis and a major source of environmental degradation, as widespread ecosystem destruction continues to unfold (Leal Filho et al., 2024a). This paper addresses this topic by studying the Ukrainian case as a large-scale instance of conflict-related environmental harm that requires systematic spatial, ecological, and legal interpretation. The conflict in Ukraine therefore provides an important case through which to examine how evidence of severe, widespread, and potentially long-term environmental damage may be documented and interpreted in relation to current debates on the possible recognition of ecocide as an international crime (Duiunova et al., 2024; Tsymbalyuk, 2025).

The term “ecocide” comes from the Greek *oikos* (house) and the Latin *caedere* (to kill), literally meaning “killing one’s home” (Gillett, 2025). The concept is not new: it has been discussed since the early 1970s, particularly in connection with the environmental consequences of the Vietnam War and the use of Agent Orange (Zierler, 2011), and later in relation to other large-scale environmental disasters and conflict-related harms. For decades, this term has been used to describe events that cause severe environmental disturbance with potential ecological implications, such as the defoliation campaign during the Vietnam War and the Chernobyl disaster (Haque et al., 2024; Wirtu and Abdela, 2025).

More recently, debates on ecocide have gained renewed attention due to increasing concern about environmental destruction in armed conflicts, including the Russia-Ukraine war, and the need to clarify whether and how such harms could be addressed through international criminal law (Haltsova et al., 2024). In a significant step, an independent expert panel drafted a legal definition in 2021 for the International Criminal Court (ICC). They suggested defining ecocide as “unlawful or wanton acts committed with knowledge that there is a substantial likelihood of severe and either widespread or long-term damage to the environment” (Minkova, 2023). In this context, “wanton” refers to reckless disregard for damage considered clearly excessive in relation to the anticipated social or military benefits. The terms “severe,” “widespread,” and “long-term” ensure that only the most serious harms, which go beyond local pollution and threaten regional stability for generations, would qualify (Minkova, 2023).

The war in Ukraine has generated multiple forms of environmental harm that are relevant to discussions on ecocide, while also illustrating the difficulty of distinguishing between environmental damage as a consequence of conflict and environmental damage as an intended target (Rawtani et al., 2022). The destruction of industrial and energy infrastructure has been especially extensive (Chowdhury et al., 2023). The bombing of the Azot chemical plant in Severodonetsk posed a risk of a catastrophic ammonia leak. Repeated strikes on oil depots have created large fires, releasing toxic smoke and contributing to serious air-pollution episodes. The assault on the Azovstal steelworks in Mariupol became a symbol of Ukrainian resistance and a potential source of contamination from the site’s industrial waste (Lai, 2025; Yutilova et al., 2025). Damage to water treatment facilities in Mariupol has contributed to disruptions in access to clean water and increased risks of waterborne diseases (Lai, 2025). Millions of hectares of agricultural land are now affected by landmines, shell fragments, cratering, and soil disturbance, creating a legacy that may hinder farming and restoration for decades. The fertile chernozem soil, one of Ukraine’s most important natural assets, is being extensively affected by physical disturbance, contamination risks, and reduced agricultural functionality (Baliuk et al., 2024).

In addition, the occupation of the Chernobyl Exclusion Zone further illustrates how military activity can create acute environmental and health risks in highly sensitive ecosystems. By digging trenches in the highly radioactive Red Forest, soldiers stirred up radioactive dust, exposing themselves and potentially spreading contamination (Balashevska et al., 2023). Additionally, the damage to Ukraine’s extensive network of nature reserves, including the Askania-Nova biosphere reserve, threatens unique plant and animal species, undermining years of conservation efforts and placing biodiversity hotspots under severe pressure (Hartmane et al., 2024). These examples demonstrate severe environmental consequences of war and highlight the evidentiary challenge at the centre of this paper, which is to document the spatial extent, severity, persistence, and ecological implications of conflict-related environmental damage.

The environmental consequences of war have been documented in a growing body of literature well beyond the specific legal framing of ecocide. Research in warfare ecology has shown that armed conflict can generate habitat destruction, biodiversity loss, toxic contamination, agricultural abandonment, water and soil degradation, and long-lasting land-system changes. Earlier studies discussed the massive pollution caused by the 1991 Gulf War, including oil well fires and marine contamination, while later work has documented conflict-related land-use and agricultural change in the Caucasus and Syria, as well as vegetation loss and ecosystem regression in Tigray. Recent studies on Ukraine have similarly highlighted damage to soil, water, air, biodiversity, and protected areas, reinforcing the need to examine war as an important driver of environmental degradation even where the term ecocide is not explicitly used. Positioning the present study within this broader literature helps demonstrate that Ukraine is part of a wider pattern of conflict-related ecological disruption, while also showing the relevance of geospatial monitoring for building comparable evidence across cases (Baumann and Kuemmerle, 2016; Leal Filho et al., 2024a; Leal Filho et al., 2024b; Leal Filho et al., 2024c; Gerges, 1993; Hazaymeh et al., 2022; Lawrence et al., 2015; Negash et al., 2023). Considering this, the war in Ukraine represents a large-scale case of conflict-related environmental degradation with significant ecological and societal implications. In this context, the spatial extent, persistence, and documented characteristics of environmental disturbance make Ukraine an important case for examining how geospatial and documentary evidence may contribute to discussions surrounding the proposed criteria associated with ecocide.

Although existing literature and institutional reports have already documented thousands of war-related environmental incidents in Ukraine (Leal-Filho et al., 2015; Leal Filho et al., 2024a; Leal Filho et al., 2024b; Leal Filho et al., 2024c), there remains a lack of integrated, empirically grounded understanding of how these incidents may be assessed against the scientific and legal criteria associated with ecocide. Current assessments tend to be either sectoral, focusing, for example, on soil, water, protected areas, or air pollution, or institutional, such as reports by the United Nations Environment Programme (UNEP), the United Nations Economic Commission for Europe (UNECE), Ukrainian governmental platforms, and civil-society monitoring initiatives. They rarely align spatially explicit evidence with the elements of the proposed international definition of ecocide, namely, severity, widespread character, and long-term effects. The literature also does not yet sufficiently clarify which specific patterns of damage, for example, compound events such as damage to industrial facilities followed by flooding, sediment mobilisation, or contamination pathways, produce the most enduring ecological harm and the highest societal costs. Finally, there is limited knowledge on how the Ukrainian case can inform future environmental accountability, compensation, restoration planning, and recovery mechanisms, including those inspired by the polluter-pays principle. A related gap concerns the absence of explicit decision rules for distinguishing general war-related environmental damage from damage that may approach ecocide-level concern. In this paper, such distinction is addressed through an indicator-based screening logic: damage is considered ecocide-relevant only when evidence suggests observable high-intensity disturbance, broad spatial distribution or cross-ecosystem effects, likely persistence beyond the immediate conflict period, and triangulation across geospatial and documentary sources.

Against this background, the research problem can be formulated as follows: despite the abundance of monitoring data, there is still no consolidated analytical framework that links observable, georeferenced environmental destruction in Ukraine to the concept of ecocide and to concrete post-war restoration requirements. The core research question emerging from this problem is: How can systematically collected geospatial and documentary evidence of war-related environmental damage in Ukraine be organised, classified, and interpreted in relation to the proposed criteria of severe, widespread, and long-term environmental harm, while also informing mechanisms for ecological recovery, accountability, and restoration planning? Addressing this question allows the study to move from descriptive accounts of damage to a more structured, evidence-based assessment of environmental disturbance, ecological risk, attribution challenges, and the prioritisation of areas and ecosystems most in need of remediation. The paper therefore does not claim to deliver a legally binding classification of ecocide. Instead, it develops a transparent analytical framework for assessing whether observed war-related environmental disturbances show characteristics that may be relevant to ecocide debates and future legal or policy assessment.

Methodologically, the study advances an integrated conflict-environment assessment framework that combines multi-source satellite platforms, open-source geospatial evidence, and qualitative documentary analysis. Geospatial and environmental methods are especially appropriate for investigating war-related environmental damage because such impacts are inherently spatial, unevenly distributed, and highly dynamic over time (Humayun, 2025; Yakymchuk et al., 2023). In conflict settings, direct field access is often restricted by insecurity, damaged infrastructure, contamination risks, landmines, or the absence of continuous monitoring systems, which makes satellite imagery, GIS-based analysis, and other environmental assessment tools particularly valuable (Altarez et al., 2024; Zwijnenburg and Ballinger, 2023). These approaches allow researchers to detect and compare changes in land cover, vegetation stress, fire scars, flooding patterns, damaged industrial sites, agricultural cratering, forest loss, and pressures on protected areas across large territories and over multiple time periods. They also provide a systematic and comparatively transparent basis for triangulating environmental change with documentary and institutional evidence. In this sense, geospatial methods are not simply a technical choice, but a methodologically suitable response to the practical and epistemic constraints of war, especially when the objective is to identify widespread, severe, and potentially long-term environmental disturbance and ecological pressure in a consistent and spatially explicit manner (Kaplan et al., 2022; Machlis and Hanson, 2008; Machlis and Hanson, 2011; Sticher et al., 2023).

To tackle the research question, the study employs a mixed-methods conflict-environment assessment design that combines geospatial analysis of multi-temporal satellite imagery and open-access environmental datasets, including Sentinel Hub EO Browser (2025), Copernicus Emergency Management Service (CEMS, 2025), NASA FIRMS (2025), Global Forest Watch, Africk's fortification dataset, and Google Earth, with a systematic qualitative review of governmental, intergovernmental, and NGO reports. Rather than treating remote-sensing outputs as direct legal evidence of ecocide, the study uses them to identify and classify observable surface disturbances, including land-cover change, fire occurrence, flooding, vegetation loss, infrastructure destruction, and soil disturbance. These observations are then triangulated with qualitative and institutional sources to contextualise events, identify environmental pathways, and assess potential implications for human health, biodiversity, ecosystem services, and environmental governance. The integration of these methods allows the study to produce a structured inventory of war-related environmental damage events, classify them according to indicative and analytically interpreted "severe," "widespread," and "long-term" criteria, and connect each class of disturbance with possible restoration and policy-response options. For operational purposes, severity is assessed through the intensity and type of observable disturbance, such as infrastructure destruction, extensive vegetation loss, flooding, fire activity, soil disruption, or potential contamination pathways; widespread character is assessed through the spatial extent of affected areas, recurrence across multiple locations, and involvement of different ecosystem types; and long-term character is assessed through persistence of disturbance, likely delayed recovery, contamination risks, or continued constraints on land, water, or ecosystem use. These criteria are applied against pre-war or pre-event baselines where available and are interpreted through triangulation with institutional reports and peer-reviewed evidence. They function as transparent analytical heuristics rather than fixed legal thresholds.

The paper is organised around three analytical levels that are important for maintaining conceptual clarity. The first level concerns observable environmental disturbance, such as land-cover change, fire activity, flooding, damaged infrastructure, or agricultural cratering. The second level concerns ecological impact or injury, including potential consequences for ecosystem structure, function, biodiversity, contamination pathways, and ecosystem services. The third level concerns legally relevant environmental harm, including harm discussed in relation to the proposed concept of ecocide. This study primarily addresses the first level through geospatial analysis and interprets the second level through supporting literature and qualitative evidence. The third level is considered only in an indicative and interpretative manner and does not constitute a formal legal assessment. This distinction is essential to avoid conflating scientific observation with legal qualification, especially given the difficulties of establishing causality, intent, knowledge, proportionality, and wantonness in conflict settings. Accordingly, the framework distinguishes between: (i) general war-related environmental damage, where environmental harm is observable but legal relevance remains uncertain; (ii) ecocide-relevant environmental damage, where severity, spatial extent, persistence, and corroborating evidence may suggest potential alignment with proposed ecocide criteria; and (iii) legally classifiable ecocide, which would require formal legal assessment beyond the scope of this paper.

The expected contribution to theory is the operationalisation of ecocide-related criteria as an empirically assessable but legally cautious category that can inform future research on conflict-related environmental harm. The contribution to methodology is a reproducible framework that combines geolocated conflict-associated events, multi-source satellite data, and qualitative environmental evidence to identify spatial patterns of damage. The contribution to practice is a decision-support approach for Ukrainian authorities and international partners to support environmental monitoring, risk-based zoning, prioritisation of green recovery investments, and the development of evidence bases for possible environmental reparations or accountability mechanisms. In short, the study helps to close the current gap between environmental monitoring and accountability-oriented assessment by showing how Ukraine's experience can inform future approaches to conflict-related environmental governance.

This study is positioned in relation to established environmental damage assessment frameworks, including the U.S. Natural Resource Damage Assessment (NRDA) process and the European Union Environmental Liability Directive (ELD), which provide structured approaches for evaluating ecological injury, determining liability, and guiding restoration. While these frameworks require detailed baseline data, quantified injury assessment, and valuation of ecosystem service losses, the present study focuses on an earlier analytical stage: the identification and spatial characterisation of conflict-associated environmental disturbances using geospatial and mixed-methods evidence. As such, the approach developed here is not intended to replace formal damage assessment procedures but to complement them by supporting impact screening, identifying priority areas for further investigation, and contributing to the evidentiary base required for subsequent ecological, legal, and policy analyses.

2 Materials and methods

This study applies a multi-method approach to assess environmental impacts associated with war-related damage in Ukraine. Locations of damage were identified and geolocated using satellite imagery, open-source information, and official reports. Environmental conditions at these locations were then analysed using remote sensing data and existing environmental datasets to evaluate the nature and extent of the observed damage. The analysis is complemented by a qualitative review of secondary data sources to support interpretation and validation of the geospatial observations. Together, these components form a conflict-environment assessment framework that (i) geolocates conflict-related events, (ii) characterises environmental conditions and observable disturbance using multi-source satellite and ancillary datasets, and (iii) integrates qualitative and institutional evidence to interpret these disturbances as conflict-associated environmental change.

2.1 Study area

The study area encompasses war-impacted regions in southern and eastern Ukraine (47.5–48.5°N, 34.5–37.5°E), spanning approximately 15,000 km^2. The primary case-study areas include the Azovstal Iron and Steel Works in Mariupol (Donetsk Oblast), the lower Dnipro River basin, and the Kharkiv–Luhansk border zone (Pishchane–Berestove). The study also incorporates the Oleshky Sands National Nature Park and adjacent floodplain areas affected by the Kakhovka Dam breach, as well as heavily damaged urban centres such as Mariupol, Severodonetsk, and Bakhmut.

While these locations represent the primary case-study areas, the analysis incorporates multi-source geospatial datasets covering a broader set of regions across Ukraine, including Kherson, Zaporizhzhia, Mykolaiv, and Donetsk oblasts, as well as processes affecting the lower Dnipro basin and the Black Sea region.

Physical geography features a semi-arid continental climate (annual precipitation 400–550 mm, winter temperatures of −15 to −25 °C, summer temperatures of 25 °C–35 °C), flat steppe topography (elevations 10–100 m), black earth and sandy soils prone to erosion, and major hydrology via the Dnipro River and Black Sea coast. The study area is also relevant in a broader regional context, as environmental impacts extend beyond national borders, particularly through hydrological and atmospheric pathways affecting the Black Sea basin.

Ecosystems include industrial coastal zones (Mariupol), riparian forests and steppe grasslands (Dnipro basin), and arid sand dunes in Oleshky Sands National Nature Park. Dominant vegetation comprises oak-hornbeam forests, psammophytic shrubs, and agricultural steppe; fauna includes vulnerable steppe species affected by habitat loss.

Anthropogenic context centers on heavy industry (Azovstal steelworks), agriculture, and critical energy infrastructure such as the Zaporizhzhia Nuclear Power Plant, with an average population density of 50–100 inhabitants per km^2 and major urban hubs like Mariupol (pre-war ~450,000 residents) and other frontline cities experiencing extensive destruction.

The relevance of the study area stems from direct and indirect effects of ongoing hostilities including shelling, bombing, clashes, and military vehicle movement–on these territories, resulting in infrastructure destruction, potential industrial pollution releases, sewage system failures contaminating aquifers, widespread fires, and ecosystem damage.

2.2 Geospatial analysis

To quantitatively map and assess the physical extent of observable environmental disturbance, this study employs geospatial analysis of satellite imagery. This approach enables the identification, documentation, and comparison of damage across large and often inaccessible areas of Ukraine.

The analysis focused on visible impacts on (i) critical infrastructure (e.g., industrial and energy facilities), (ii) agricultural land (e.g., fires, cratering, and soil disturbance), and (iii) natural ecosystems (e.g., forest fires and wetland degradation). Multi-temporal satellite imagery was used to detect changes over time and to establish a timeline of environmental disturbances affecting land cover, soil, and water systems.

In addition, it should be noted that the geospatial analysis does not establish direct causality between observed environmental changes and military activity in all cases. The identified patterns represent spatial and temporal associations that may also reflect pre-existing land-use practices, climatic variability, and legacy environmental conditions such as industrial pollution. To address this limitation, the interpretation is supported through triangulation with qualitative and institutional data sources. However, varying levels of attribution uncertainty remain, particularly in dynamic or data-sparse contexts.

The geospatial analysis applied in this study primarily addresses observable environmental disturbance, while ecological impacts are interpreted through supporting literature and qualitative evidence. Any consideration of legally relevant environmental harm remains indicative and does not constitute a formal legal assessment.

The geospatial analysis applied in this study primarily captures surface-level disturbances, including land-cover change, fire occurrence, flooding, and infrastructure damage. These indicators provide evidence of environmental pressure but do not, on their own, constitute direct measurement of ecological injury, which requires site-specific data on contamination levels, ecosystem function, and service loss.

Accordingly, the approach adopted in this study should be understood as an initial analytical stage that supports impact screening and spatial prioritisation, rather than a full ecological damage assessment as defined under NRDA or ELD frameworks. The geospatial assessment was conducted using several open-access remote sensing platforms and datasets, including Sentinel Hub EO Browser (Sentinel-2 optical imagery, 10–20 m spatial resolution), NASA FIRMS (MODIS and VIIRS thermal anomaly data for active fire detection), Copernicus Emergency Management Service (CEMS, satellite-based rapid mapping products), Global Forest Watch (tree cover loss and gain data derived from Landsat imagery, 30 m spatial resolution), Africk's fortification dataset (high-resolution satellite-based conflict mapping), and Google Earth (very high-resolution optical imagery for visual validation).

For each case-study area, satellite imagery was manually retrieved by selecting geographic coordinates, temporal range (pre- and post-event periods), and appropriate sensors within each platform. For Sentinel-2 data, cloud-free images were prioritised, and standard false-colour composites (e.g., near-infrared bands) were used to enhance the detection of vegetation loss and burned areas.

Thermal anomaly data from NASA FIRMS were used to identify active fire locations and temporal patterns of fire occurrence. However, these data represent active fire detections rather than burned area extent and therefore do not allow precise attribution of ignition sources.

CEMS products were used to validate large-scale events such as flooding, while Global Forest Watch data supported the identification of forest cover change.

The analysis was based on visual interpretation and comparative assessment of time-series imagery. Environmental disturbances were identified through changes in surface characteristics, including vegetation loss, burn scars, flooding, infrastructure destruction, and terrain disturbance.

Events were included in the analysis when at least one of the following conditions was met: (i) clearly detectable land cover change between temporal images, (ii) presence of thermal anomalies indicating fire events, or (iii) visible structural damage to infrastructure. Where possible, observations were cross-checked across multiple datasets (e.g., satellite imagery and fire detection platforms) to improve consistency and reduce interpretation bias.

This workflow provides a transparent and reproducible approach for identifying and comparing environmental damage patterns based on publicly accessible geospatial data.

2.3 Qualitative analysis of secondary data sources

To complement the geospatial analysis, a qualitative analysis of secondary data sources was conducted to provide contextual and interpretative support for the observed environmental changes.

The analysis covered reports and publicly available documentation published between 2022 and 2025 by Ukrainian governmental institutions, international organisations (e.g., UNEP, OSCE, World Bank), and non-governmental organisations (NGOs) involved in monitoring environmental impacts of the conflict.

Documents were selected using purposive sampling based on their relevance to environmental damage, including pollution incidents, ecosystem degradation, infrastructure destruction, and impacts on human health and biodiversity.

A qualitative thematic content analysis approach was applied to identify recurring themes and categories of environmental impact, such as soil contamination, water pollution, forest loss, and air pollution. The review also provided contextual descriptions of specific events, supporting the interpretation of satellite-based observations.

The integration of geospatial and qualitative data was performed through triangulation. Spatial observations were systematically compared with documented evidence to verify the location, type, and characteristics of environmental damage.

This combined approach allows the study to capture both large-scale spatial patterns and the detailed context of individual events. To reduce potential bias, multiple sources were systematically cross-checked, and qualitative information was used to support and contextualise geospatial observations rather than to independently determine environmental impacts.

In this study, the criteria of "severe," "widespread," and "long-term" environmental damage are operationalised using indicative and interpretative spatial and temporal proxies derived from geospatial data and supporting evidence. "Severity" is interpreted in relation to the intensity of observable disturbance (e.g., infrastructure destruction, vegetation loss, contamination indicators), "widespread" refers to the spatial extent of impacts across regions and ecosystems, and "long-term" is inferred from the persistence of damage and the likelihood of prolonged ecological recovery.

These criteria are applied as analytical heuristics rather than fixed quantitative thresholds, due to current data limitations and the absence of universally standardised metrics in conflict settings. The approach therefore supports comparative assessment and pattern identification, but does not constitute a formal legal classification of ecocide.

3 Results and discussion

The results and discussion section is organised in three complementary strands. Section 3.1 uses multi-source geospatial data to map the spatial distribution and typology of war-related environmental disturbance across Ukraine. Section 3.2 then examines how these pressures may contribute to impacts on soils, aquatic systems, the atmosphere, forests, and biodiversity. Finally, Section 3.3 synthesises qualitative evidence from international, national, and civil-society sources to corroborate and contextualise the geospatial and ecological findings.

3.1 Spatial distribution of environmental damage

To systematically assess the spatial distribution and extent of war-related environmental damage in Ukraine, the analysis relied on international satellite and open-source remote sensing platforms (Bachmann-Gigl and Dabiri, 2024). These systems provide verified, large-scale, and regularly updated data on land cover change, fires, flooding, and terrain deformation (Zhao and Morikawa, 2025). The selected datasets combine optical, radar, and thermal imagery, enabling a consistent and comparative view of environmental transformation over time (Supplementary Table S1). While these datasets enable robust detection of spatial patterns of environmental disturbance, they primarily reflect observable surface changes and should not be interpreted as direct evidence of ecological injury or quantified environmental damage. Building on these datasets, the geospatial analysis identified six main categories of visible environmental disturbance, derived from patterns consistently observable in multi-temporal satellite imagery (Supplementary Table S2). These categories are derived from observable spatial patterns and should be interpreted as indicators of environmental change associated with conflict dynamics, rather than as definitive attribution to specific causal mechanisms.

This typology reflects both the physical diversity and the potential ecological implications of war-related impacts across Ukraine's landscapes. Each category is further illustrated and analysed in the subsequent figures and descriptions (Figures 1–6). In this context, the typology can also serve as a preliminary tool for spatial prioritisation, supporting the identification of areas where more detailed ecological assessment, risk evaluation, and restoration planning may be required. At this stage, the analysis focuses on observable physical disturbances. The translation of these disturbances into ecological impacts or legally relevant environmental harm is addressed in subsequent sections and should not be inferred directly from geospatial patterns alone.

3.1.1 Industrial and energy facilities

The Sentinel-2 satellite imagery (Sentinel Hub EO Browser, 2025) illustrates the transformation of the Azovstal Iron and Steel Works area in Mariupol between 2021 and 2025 (Figure 1). The comparison is based on images acquired for the same geographic location (47.099°N, 37.604°E).

Before the invasion (Figure 1a, August 2021), the industrial complex appeared as a well-defined infrastructure zone with characteristic geometric structures, organised road networks, and storage areas along the coastline of the Sea of Azov. By 2025 (Figure 1b, August 2025), the same area exhibits extensive surface darkening and structural collapse, representing typical signatures consistent with severe bombardment, fire damage, and prolonged industrial degradation.

The previously regular spatial organisation of the plant is replaced by irregular debris fields, fragmented structures, and burnt zones, indicating the near-total destruction of production facilities and storage infrastructure. These changes reflect a profound transformation of the industrial landscape and are consistent with severe physical disturbance. While satellite imagery does not allow direct quantification of pollutant release, the observed spatial patterns suggest a high likelihood of environmental risks associated with industrial residues and damaged infrastructure.

3.1.2 Hydrological disruptions and flooded areas

Hydrological disruptions represent one of the most severe forms of environmental transformation caused by the war. The destruction of hydraulic infrastructure–particularly large dams and reservoirs–has resulted in massive flooding, river course

FIGURE 1
Sentinel-2 satellite images of the Azovstal Iron and Steel Works area (Mariupol, Ukraine; 47.099°N, 37.604°E, scale bar: 500 m). **(a)** August 2021 – pre-war industrial landscape with intact infrastructure; **(b)** August 2025 – post-war conditions showing extensive structural destruction, fire damage, and surface darkening. Data source: Sentinel Hub EO Browser (accessed November 2025).

alteration, and the subsequent desiccation of formerly inundated territories (Shumilova et al., 2025).

The map provided by the Emergency Response Coordination Centre (ERCC, 2023), based on Copernicus Emergency Management Service (CEMS, 2025) satellite data, shows the spatial extent and distribution of flooded areas following the destruction of the Kakhovka Dam on 6 June 2023 (Figure 2). The inundated area extended over approximately 620 km^2, affecting settlements, agricultural land, and wetlands across the Kherson and Mykolaiv regions. The map indicates that flooding was concentrated along the Dnipro River floodplain, with the most extensive inundation occurring in low-lying downstream areas.

The spatial pattern of flooding suggests not only the rapid expansion of water across the floodplain but also potential pathways for the redistribution of sediments and contaminants. Floodwaters may have contributed to the redistribution of industrial pollutants, agrochemicals, and contaminated sediments, although the relative contribution of pre-existing contamination and conflict-related inputs remains uncertain.

High-resolution Planet Labs imagery published by Africk (2025) captures the hydrological transformation in near real time. The image from 4 June 2023 shows the dam structure and reservoir still intact, with visible fortifications on the southern bank. By 6 June 2023, the post-destruction image reveals a complete breach of the dam and extensive downstream flooding.

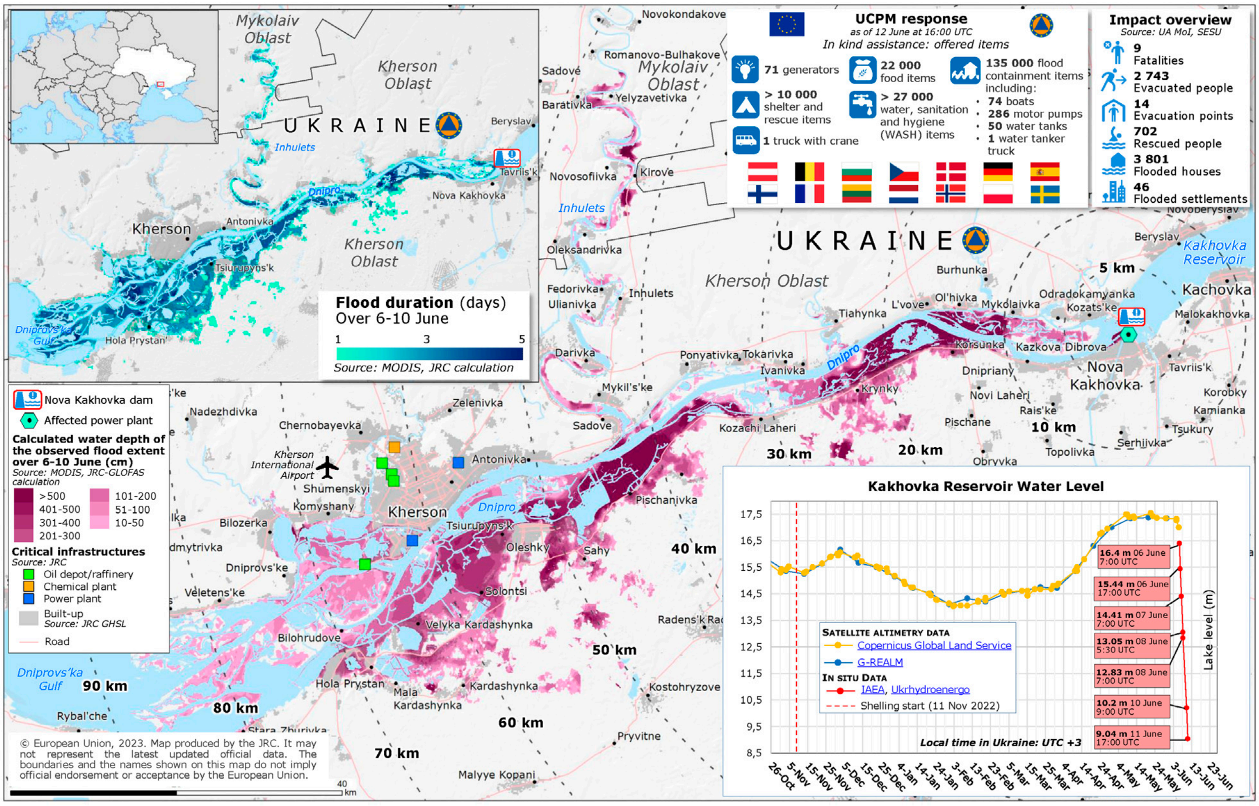

FIGURE 2
Spatial extent of flooding following the destruction of the Kakhovka Dam (6–10 June 2023), based on Copernicus Emergency Management Service (CEMS) satellite data. Flooded areas (blue) indicate the spread of water across settlements, agricultural land, and floodplain ecosystems in the lower Dnipro region. Data source: ERCC (2023), based on CEMS mapping.

Rather than a gradual change, the comparison of the images published by Africk (2025) illustrates an abrupt reconfiguration of the hydrological system. The rapid expansion of water coverage between the two dates highlights the sudden loss of flow control and the immediate downstream propagation of floodwaters. These observations indicate altered water flow regimes and sediment dynamics, with potentially cascading environmental effects.

These visual data provide evidence of environmental disturbance and indicate potential consequences of the Kakhovka Dam collapse, while also indicating the onset of longer-term degradation processes. Subsequent satellite observations document sedimentation, salinisation, and vegetation loss, marking the transition from acute flooding to more persistent land degradation across southern Ukraine (Shumilova et al., 2025).

3.1.3 Wildfires on forest and agricultural lands

Wildfires represent one of the most spatially extensive forms of war-related environmental degradation (Yailymov et al., 2023). Satellite data from NASA FIRMS indicate a sharp increase in fire activity along active frontline zones in the Donetsk, Zaporizhzhia, and Kherson regions (Figure 3).

The maps presented in Figure 3, based on two-week periods in early June 2021–2024, show a clear transition from relatively dispersed fire activity in 2021 to highly concentrated and spatially clustered fire hotspots in 2022–2024, particularly along frontline areas. The increasing density and persistence of these clusters suggest repeated burning events rather than isolated seasonal fires.

Between 2021 and 2024, large areas of land were affected by recurrent fires, many of which are spatially associated with areas of active hostilities, although the available data do not allow direct attribution of ignition sources (Karamushka et al., 2025). The time-series analysis highlights a spatial shift in fire activity, with the densest and most persistent clusters occurring in areas of prolonged hostilities.

However, FIRMS data represent active fire detections rather than burned areas and do not allow precise attribution of ignition sources; therefore, the observed patterns should be interpreted with caution.

These fires not only affected forest and agricultural lands but also may have contributed to the release of significant volumes of carbon and particulate matter, contributing to regional air pollution and transboundary smoke transport across southern and eastern Europe (Kussul et al., 2023).

3.1.4 Agricultural land degradation and cratering

The agricultural landscapes along the Pishchane–Berestove corridor, located on the boundary between Kharkiv and Luhansk

(a) 1–14 June 2021

(b) 1–14 June 2022

(c) 1–14 June 2023

(d) 1–14 June 2024

FIGURE 3
Spatial distribution of active fire detections (thermal anomalies) across Ukraine based on NASA FIRMS data for selected two-week periods in June 2021–2024 (44–52°N, 22–40°E; scale bar: 100 km). Red points indicate fire hotspots derived from MODIS and VIIRS sensors. The maps illustrate a shift from dispersed fire activity in 2021 (pre-conflict baseline) to dense and spatially clustered patterns in 2022–2024, particularly along frontline regions in eastern and southern Ukraine. Data source: NASA FIRMS (accessed November 2025). **(a)** 1–14 June, 2021. **(b)** 1–14 June, 2022. **(c)** 1–14 June, 2023. **(d)** 1–14 June, 2024.

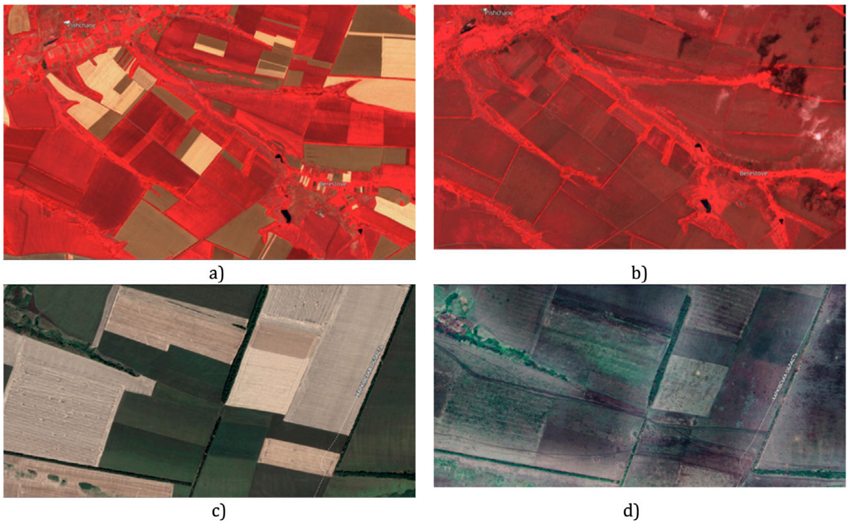

FIGURE 4
Comparison of war-related agricultural land degradation in the Pishchane–Berestove area (Kharkiv–Luhansk border, Ukraine; 48.9°N, 38.2°E; scale bar: 400 m). **(a,b)** Sentinel-2 false-colour (NIR) imagery for 2020 and 2024, showing the transition from intact cropland with continuous vegetation cover to fragmented fields with burned areas, trenches, and disrupted soils; **(c,d)** Google Earth high-resolution optical imagery for 2020 and 2024, highlighting the emergence of extensive artillery cratering, trench networks, and widespread surface damage not present before the conflict. Data sources: Sentinel Hub EO Browser; Google Earth (accessed November 2025).

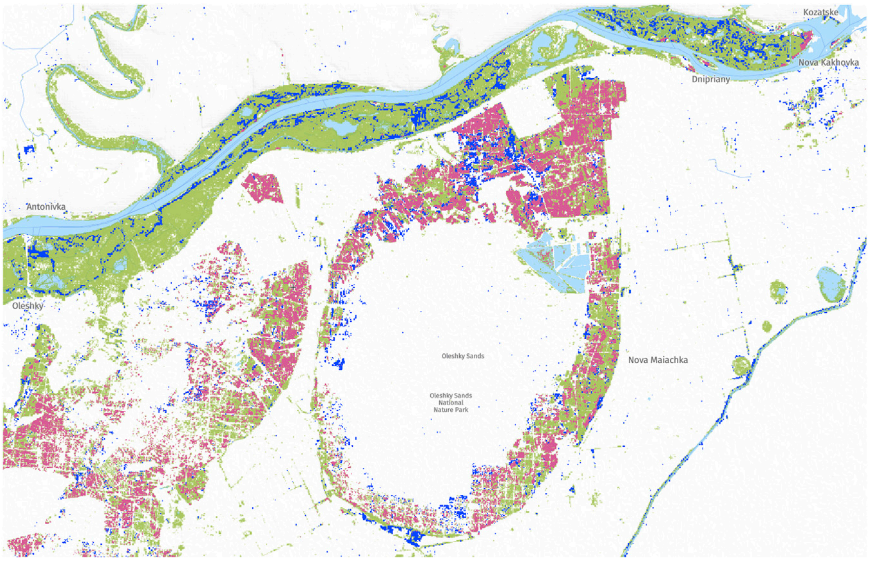

FIGURE 5
Forest cover change (2001–2024) in the lower Dnipro basin, including Oleshky Sands National Nature Park (46°38′N, 33°05′E; scale bar: 5 km). Red areas indicate tree cover loss, blue areas indicate tree cover gain, and green areas represent vegetation regrowth, particularly in floodplain areas affected by the Kakhovka Dam breach in 2023. The map illustrates the spatial coexistence of forest degradation and vegetation recovery processes. Data source: Global Forest Watch (accessed November 2025).

oblasts (48.9°N, 38.2°E), show extensive war-related degradation. Comparative analysis (Figure 4) of Sentinel-2 false-colour imagery for 2020 (Figure 4a) and 2024 (Figure 4b) (Sentinel Hub EO Browser, 2025), together with high-resolution optical data from Google Earth (Google Earth, 2025) for the same years (Figures 4c,d), reveals a clear transformation from stable, cultivated cropland to heavily cratered and structurally disrupted terrain.

Between 2020 and 2024, satellite imagery shows a transition from intact, evenly vegetated agricultural fields with preserved boundaries and shelterbelts to a landscape marked by severe war-related degradation. By 2024, vegetation is fragmented, burned areas and fresh shell impacts appear as dark patches, and extensive trench lines and soil scars indicate sustained military activity (Figures 4a,b). High-resolution imagery

FIGURE 6
Destruction of urban and industrial infrastructure in Mariupol, Ukraine (47°06′N, 37°38′E; scale bar: 200 m). **(a)** 2021 – pre-war urban structure; **(b)** 2023 – post-destruction conditions showing extensive demolition of residential and industrial zones, collapse of transport infrastructure, and expansion of debris-dominated “grey zones.” Data source: Google Earth (accessed November 2025).

confirms that no such disturbances were present in 2020, whereas the 2024 scene contains numerous artillery craters, eroded shelterbelts, and widespread surface disruption consistent with repeated shelling and heavy machinery movement (Figures 4c,d).

These changes indicate a substantial loss of land-use functionality and structural integrity of agricultural systems. The observed patterns are consistent with repeated physical disturbance and may have long-term implications for soil stability and agricultural productivity. These transformations are consistent with direct physical disturbance processes, although the contribution of pre-existing land-use conditions and environmental degradation cannot be fully excluded. As observed in other war-affected agricultural zones in eastern Ukraine, these cumulative effects may contribute to long-term declines in soil fertility, crop yield, and overall landscape stability.

3.1.5 Forest loss and damage to protected areas

Protected areas and forest ecosystems in southern Ukraine have been severely affected by the combined impacts of warfare, fires, and hydrological disturbances. The Oleshky Sands National Nature Park, one of the country’s most unique semi-desert landscapes, illustrates this cumulative degradation (Figure 5).

Satellite data from Global Forest Watch (Global Forest Watch, 2025) show extensive forest cover loss (shown in red) across the park and surrounding territories, primarily caused by large-scale wildfires during 2022–2024 (Figure 5). These fires destroyed vast pine plantations that once stabilised the sandy terrain, accelerating processes of deforestation, soil erosion, and desertification.

At the same time, areas adjacent to the Dnipro floodplain display signs of vegetation recovery. Tree cover gain (shown in blue) and broader vegetation regrowth zones (shown in green) have emerged following the Kakhovka Dam flooding in 2023.

The coexistence of forest loss and vegetation gain reflects the spatial heterogeneity of environmental change in conflict-affected areas. This suggests that degradation and recovery processes may occur simultaneously, depending on local disturbance regimes. This contrast highlights the dual nature of environmental transformation–destruction of forests in the uplands and spontaneous greening in newly inundated zones.

3.1.6 Urban and infrastructural destruction

Urban and infrastructural destruction represents one of the most visible and socially devastating manifestations of war-related environmental damage in Ukraine. Large-scale bombardments have reduced entire districts of Mariupol, Severodonetsk, and Bakhmut to rubble, affecting housing, schools, hospitals, transport nodes, and energy infrastructure. These urban "grey zones" – vast areas dominated by ruins, debris, and residual contamination–illustrate the intersection between environmental, social, and public-health challenges.

The destruction of reinforced concrete structures and industrial facilities has generated large volumes of mixed waste, potentially containing asbestos, heavy metals, and petroleum derivatives, posing long-term risks to soil and groundwater. In parallel, damage to heat and power plants has disrupted municipal energy supply, while failures in sewage and water infrastructure have likely contributed to untreated discharges into surface waters, further aggravating environmental pressures.

The historical imagery presented in Figures 6a,b illustrates the scale of destruction in Mariupol between 2021 and 2023, showing the transition from a densely built industrial port city to a heavily damaged urban landscape. The transformation of urban areas into debris-dominated environments highlights the extent of infrastructural disruption and suggests increased environmental risks associated with construction materials and damaged utility systems.

Taken together, the identified patterns represent indicators of environmental disturbance rather than direct measurements of ecological injury. The translation of these disturbances into ecological damage depends on additional factors, including contamination pathways, ecosystem sensitivity, and recovery capacity. The geospatial evidence indicates consistent patterns of environmental change spatially associated with areas of military activity, although precise causal attribution remains subject to uncertainty. The scale and persistence of these impacts are broadly consistent with characteristics often described as "severe, widespread, and long-term damage", based on indicative spatial and temporal patterns observed in the data, although this correspondence is indicative and does not constitute a formal legal classification.

3.2 Environmental impacts on ecosystems

The interpretation of environmental impacts in conflict settings requires careful consideration of causal attribution. While many of the observed environmental changes coincide spatially and temporally with military activity, the analysis does not assume direct causality in all cases. Instead, the findings reflect conflict-associated environmental change, acknowledging that other factors–including pre-existing land-use patterns, climatic variability, and legacy environmental conditions–may also contribute to the observed impacts. In particular, the assessment of ecosystem service loss, recovery trajectories, and restoration endpoints remains beyond the scope of the present analysis and requires integration with additional ecological, economic, and field-based data. This approach reduces the risk of confirmation bias by explicitly distinguishing between spatial correlation and causal inference.

Within this context, it is important to distinguish between disturbance-based indicators derived from remote sensing and the concept of ecological injury as defined in environmental damage assessment frameworks. While disturbance signals provide valuable spatial evidence, the assessment of injury requires additional data on ecosystem structure, function, and service loss, which are only partially captured in this study.

The geospatial analysis primarily captures surface-level disturbances, which serve as indicators of potential environmental pressure but do not, on their own, constitute direct evidence of ecological injury or legally defined harm. This distinction is essential to avoid conflating scientific observation with legal interpretation and to maintain analytical clarity between environmental processes and their potential legal qualification.

The Russian invasion of Ukraine has generated a cascade of environmental impacts that extend far beyond the immediate destruction of infrastructure. Its ecological consequences are visible across soils, waters, the atmosphere, and living systems, affecting both local and transboundary environmental security (UNEP, 2022). At the same time, the full magnitude of these impacts remains difficult to quantify due to restricted field access, reliance on remote sensing and secondary reports, and the overlap of war-related damage with pre-existing environmental pressures.

Recent research and field observations indicate that the war represents not only a humanitarian and economic crisis but also an ecological one of exceptional scale and potentially long duration. While advances in Earth observation enable more systematic assessment of environmental damage, important limitations remain, including cloud cover, sensor resolution, incomplete ground validation, and a stronger sensitivity to visible surface disturbance than to subsurface or long-term ecological change (Dietrich et al., 2025; Marcantonio and Field, 2025). Taken together, the results provide a spatially explicit indication of environmental pressure and potential ecological impact, which may inform subsequent stages of damage assessment, including detailed injury evaluation, ecosystem service quantification, and restoration planning within established frameworks.

3.2.1 Soil degradation and contamination in war-affected areas

Recent field and laboratory investigations have revealed widespread heavy-metal contamination and extensive physical degradation of soils throughout the conflict-affected territories of Ukraine. UNEP (2022), UNEP (2023) reports that explosions, shell cratering, and the continuous movement of heavy armored vehicles have caused severe soil compaction, erosion, and the loss of fertile topsoil. These disturbances have substantially reduced water infiltration, soil aeration, and the natural regenerative capacity of ecosystems. According to UNEP (2023), nearly 30,000 km^2 of land remain potentially mined, rendering 20%–30% of Ukraine's most fertile chernozem soils inaccessible for cultivation, even within territories that have already been liberated.

Expanding upon these findings, Dmytruk et al. (2022) estimate that approximately 146,000 km^2 – around one-quarter of Ukraine's total land area–have been occupied or directly affected by military operations, with more than 90% of these territories comprising highly fertile chernozem and kastanozem soils. Although such black soils are renowned for their resilience and capacity for self-healing, the authors caution that natural recovery could span several decades due to persistent compaction, contamination, and structural disruption. They further note that roughly 90,000 km^2 of land remain mined or otherwise unsuitable for agricultural use, and that effective rehabilitation will require minimising mechanical disturbance and rebuilding soil organic matter through carefully planned ecological restoration and biotechnological interventions.

Complementary assessments by the State Ecological Inspection of Ukraine reveal the growing scale of environmental damage. Between February 2022 and January 2024, more than 280,000 m^2 (0.28 km^2) of soils were recorded as contaminated with hazardous substances, while approximately 12.3 million m^2 (12.3 km^2) of land were littered with debris, ammunition, and other remnants of warfare (Novakovska et al., 2025). Together, these findings provide substantial evidence of the severe and systemic transformation of Ukraine's soil cover, underscoring the urgent need for coordinated national and international efforts to restore the integrity and productivity of war-damaged landscapes.

These findings indicate that soil degradation is not only a localised effect of direct disturbance but may represent a systemic risk to agroecosystem functioning. However, the spatial distribution and long-term persistence of contamination remain uneven and require further site-specific investigation.

Detailed soil studies in frontline regions document widespread enrichment of potentially toxic elements, medium-to-high ecological risk indices, and combined mechanical, physicochemical, and biological disturbance conceptualised as "military-induced soil degradation" (Baliuk et al., 2024; Novakovska et al., 2025; Samilyk and Synenko, 2025; Solokha et al., 2024; Yashchenko et al., 2025; see Supplementary Material S1 for detailed concentrations and risk indices).

UNEP (2023) cautions that metallic fragments, unexploded ordnance, and infrastructure debris will continue releasing contaminants long after conflict cessation, substantially prolonging ecosystem recovery timelines. These figures underscore the necessity for comprehensive, spatially explicit soil-monitoring frameworks to delineate degradation extent and prioritise restoration interventions. Collectively, this evidence provides a basis for formulating Ukraine's long-term soil-rehabilitation strategy and safeguarding agroecosystem resilience.

3.2.2 Hydroecological consequences of the war: the transformation of aquatic systems

Among the environmental dimensions affected by Russia's full-scale invasion of Ukraine, aquatic systems have sustained some of the deepest and most enduring impacts. The destruction of hydraulic infrastructure, attacks on industrial and energy facilities, and the collapse of wastewater treatment networks have profoundly altered hydrological regimes and contaminant dynamics across large river basins. According to assessments by UNEP (2022) and the Organisation for Security and Co-operation in Europe (OSCE, 2023), verified incidents since February 2022 include damage to dams, fuel depots, and wastewater plants that triggered the uncontrolled release of pollutants into surface and groundwater. These disruptions illustrate how warfare reshapes fluvial systems far beyond combat zones, endangering public health and destabilising aquatic ecosystems on a regional scale. These patterns suggest that hydrological disruption functions as a key pathway through which local damage propagates across larger spatial scales. In this context, river systems act not only as affected components but also as vectors of environmental risk.

The destruction of the Kakhovka Dam on 6 June 2023 – which drained an 18 km^3 reservoir, flooded more than 600 km^2 of the lower Dnipro floodplain, and disrupted water supply and irrigation across extensive agricultural areas–illustrates how a single wartime event can trigger cascading hydro-ecological and socio-economic impacts (Shumilova et al., 2023; UNEP, 2023; World Bank, the Government of Ukraine, the European Union, and the United Nations, 2023; see Supplementary Material S2 for detailed hydrological and impact metrics).

Field analyses by the Arnika Association and Clean Air for Ukraine in 2023; Petrlik et al., 2024) found that the exposed bottom sediments contained elevated concentrations of lead, cadmium, nickel, arsenic, polycyclic aromatic hydrocarbons (PAHs), petroleum products, and other toxic chemicals, often exceeding indicative remediation thresholds of the EU Water Framework Directive. These data confirm the persistence of a toxic legacy that threatens to remobilise through wind erosion, runoff, and downstream sediment transport. As these pollutants are gradually transferred along the Dnipro River system, they ultimately reach the north-western sector of the Black Sea. This indicates that war-related impacts extend beyond immediate flood zones and may contribute to cumulative downstream and transboundary environmental pressures. However, the magnitude and duration of these effects remain difficult to quantify. In these environments, sediment-bound pollutants accumulate in deltaic and near-shore zones, amplifying existing environmental risks. Although native biota of the Black Sea region has historically exhibited a degree of evolutionary tolerance to environmental fluctuations, the combined effects of pollutant loading, habitat alteration, climate change, and biological invasions pose cumulative stress that may undermine ecosystem resilience and recovery potential (Kvach et al., 2025).

Pre-war monitoring already indicated significant accumulation zones of microplastics within the Dnipro basin, particularly downstream of urban wastewater outlets (Iemelianov et al., 2023; Strokal et al., 2022). The mobilisation of formerly trapped sediments is therefore expected to increase both microplastic and chemical fluxes to coastal environments, aggravating eutrophication and ecosystem stress.

The collapse of wastewater infrastructure throughout conflict-affected territories has further intensified aquatic degradation. Extended power outages and structural damage in cities such as Mykolaiv and Mariupol repeatedly disrupted sewage treatment operations, resulting in uncontrolled releases of untreated effluent and contamination of shallow aquifers (UNEP, 2022; OSCE, 2023).

These failures have elevated nutrient loads and microbial pollution, raising long-term concerns for drinking-water safety and human health (Shumilova et al., 2023; Shumilova et al., 2025).

The available evidence points to a shift from localised hydrological disturbance to broader basin-scale transformation, although uncertainties remain regarding long-term system recovery.

3.2.3 Atmospheric pollution and transboundary emission dynamics

Air pollution has become a defining environmental manifestation of the war in Ukraine, arising from large-scale fires, explosions, and the destruction of industrial and energy infrastructure. The burning of fuel depots, oil refineries, industrial plants, and urban structures has released substantial quantities of soot, fine particulate matter (PM2.5 and PM10), nitrogen oxides (NOx), sulfur dioxide (SO_2), and volatile organic compounds into the atmosphere (UNEP, 2022; Zalakeviciute et al., 2022). These war-related emissions have produced pronounced short-term episodes of degraded air quality, particularly in heavily industrialised eastern and central regions, while contributing to an overall deterioration of regional air quality (Nadtochii et al., 2023; Savenets et al., 2023).

Satellite analyses based on Copernicus Sentinel-5P data and Copernicus Atmosphere Monitoring Service (CAMS) products document extensive plumes of NO_2, aerosols, and combustion products from large industrial and fuel-storage fires. These plumes have been transported over wide areas and across national borders, confirming the transboundary nature of wartime emissions (CAMS, 2024). This indicates that air pollution associated with the conflict is not spatially confined and may affect regions far beyond immediate combat zones. At the same time, the episodic nature of emissions complicates precise attribution and long-term assessment. Many pollution episodes coincided with uncontrolled wildfires triggered by shelling or landmines in forest and steppe zones, further amplifying the release of aerosols and greenhouse gases (Savenets et al., 2023; Boychenko S. G. et al., 2025; Boychenko S. et al., 2025).

The destruction of industrial sites and petroleum facilities has generated massive air emissions, estimated at tens of millions of tonnes of CO_2 equivalents during the first year of full-scale war, and has markedly altered concentrations of particulate matter and toxic combustion products (Zalakeviciute et al., 2022). According to de Klerk et al. (2023), total greenhouse gas emissions attributable to the first 12 months of the war reached approximately 120 million t CO_2-eq. These emissions pose significant public-health risks, particularly increased respiratory and cardiovascular stress among exposed populations, and undermine progress towards regional and global climate-mitigation targets (Zalakeviciute et al., 2022; Hryhorczuk et al., 2024). From a climatic standpoint, the combustion of carbon-rich materials and vegetation represents a substantial additional source of greenhouse gases in Eastern Europe, contributing to both air quality deterioration and short-term warming effects (Hryhorczuk et al., 2024; de Klerk et al., 2023; see Supplementary Material S3).

Overall, the available evidence indicates that atmospheric impacts operate at both local and regional scales, with implications for public health and climate processes, although their cumulative effects remain uncertain.

3.2.4 Forests and biodiversity

During armed hostilities, forest ecosystems–including protected areas–are transformed into functional military spaces, significantly amplifying the risks of fires, habitat destruction, and biodiversity loss. This reflects a functional shift from conservation and regulation roles toward disturbance-driven dynamics, with potentially long-term implications for ecosystem resilience and recovery capacity.

Forests used to conceal personnel and equipment are continuously exposed to shelling, explosions of various munitions, missile strikes, aircraft crashes, ignition of military vehicles, deliberate burning of dry vegetation, movement of heavy machinery, construction of fortifications, uncontrolled logging, and contamination with fuel, lubricants, and military debris. These pressures increase the pyrogenic load, generate large volumes of combustible material, and convert forest litter into highly flammable substrates.

In active combat zones, where fire suppression is often impossible due to security constraints, wildfires spread rapidly and remain uncontrolled for extended periods. Under favourable meteorological conditions, they affect vast areas, including nature reserves and other protected territories, causing large-scale mortality of plants, invertebrates, and vertebrates, and destroying critical microhabitats for rare, endemic, and Red List species (Elbakidze et al., 2025). Combustion of biomass and military materials results in major emissions of greenhouse gases and toxic compounds, which can be transported over long distances, contributing to transboundary air pollution and climate impacts. During the first 214 days of the full-scale invasion, forest fires in temporarily occupied and frontline regions of Ukraine affected about 496 km^2 and resulted in approximately 14.3 million t of CO_2 emissions (Ecoaction, 2025).

Mechanical damage from bullets, shell fragments, blast waves, soil compaction, trenching, and repeated vehicular traffic reduces the vitality of trees and shrubs, increases their vulnerability to pests and pathogens, and elevates subsequent fire risk. Burned and disturbed stands are prone to outbreaks of insect pests and pathogenic fungi, which hinder natural regeneration and alter successional pathways. Degradation of the herbaceous layer and forest floor contributes to habitat fragmentation, a decline in floristic richness, and the loss of populations of rare plant species. Combined with chemical and physical contamination, these processes undermine soil quality and disrupt key ecosystem functions, further weakening the regulatory, protective, and sanitary roles of forest ecosystems (Krushelnitsky et al., 2016).

In this context, the assessment of war-related environmental damage has become a strategic priority, particularly for forest and protected areas. An important advance is the ecosystem-based approach proposed by Didukh (2022) and Didukh et al. (2025), which evaluates biodiversity damage using an integrated scoring system based on degree of disturbance, ecosystem resilience, and vulnerability. The application of such approaches enables more precise and scientifically grounded estimation of losses, strengthens accountability for environmental damage, and supports post-war restoration planning.

The available evidence indicates increasing fragmentation and destabilisation of forest ecosystems, although recovery pathways are likely to vary depending on disturbance intensity and post-conflict management.

3.3 Evidence from qualitative sources

Russia's full-scale invasion has generated an extensive system for monitoring environmental impacts, involving diverse methodologies and numerous national and international institutions. The UNEP (2022) plays a central role, with its Preliminary Review of the Environmental Impact of the Conflict in Ukraine documenting over two thousand verified cases of damage, including industrial spills, agricultural contamination, deforestation, soil degradation, and water pollution. UNEP's Rapid Environmental Assessment of the Kakhovka Dam Breach (UNEP, 2023) further details the consequences of the dam's destruction, including basin desiccation, loss of aquatic and riparian ecosystems, soil degradation, contamination of water resources, and risks to irrigation systems, drinking-water infrastructure, and the Zaporizhzhia Nuclear Power Plant. Transboundary effects on the Dnipro River are also highlighted. Large-scale assessments by the World Bank, the European Union, and the Government of Ukraine through the Rapid Damage and Needs Assessment (World Bank, the Government of Ukraine, the European Union, and the United Nations, 2023), and Grygaski (2023), in a report hosted by the UNECE, describes severe soil and groundwater contamination and the collapse of monitoring capacity. The OSCE (2023) similarly records extensive toxic and construction waste arising from strikes on industrial and energy facilities.

At the national level, the Operational Headquarters of the State Environmental Inspectorate oversees documentation of war-related environmental losses. The Ministry of Environmental Protection and Natural Resources reports more than 2,300 verified cases logged on the EcoZagroza platform (EcoZagroza, 2023). Complementary datasets from the Kyiv School of Economics (KSE) "Russia Will Pay" project (2022–2024) provide open-source evidence across industrial, agricultural, and residential sectors (KSE, 2025). Government reports confirm widespread destruction of energy, waste-management, and storage infrastructure. International and Ukrainian NGOs–including PAX for Peace (PAX, 2025), Conflict and Environment Observatory with Zoï Environment Network (CEO and ZEN, 2024), and IMPACT Initiatives–supply additional open-source, satellite, and field-derived analyses. Ukrainian civil-society organisations such as Ecoaction (Ecoaction, 2022) and Environment-People-Law (EPL, 2024) document air, soil, and water pollution in regions including Zaporizhzhia, Dnipro, and Kharkiv. The Ukrainian War Environmental Consequences Work Group (UWEC Work Group, 2022) regularly publishes syntheses of official statistics, remote-sensing data, and local observations.

International initiatives record over a thousand incidents of harm, with national and independent datasets mapping more than two thousand affected locations. Pollution sources include explosions, fires, chemical leaks, and debris containing asbestos, heavy metals, and unexploded ordnance. The collapse of the Kakhovka Dam in June 2023 remains the most severe single event. UNEP (2023) estimates that around 18 km^3 of water inundated 600 km^2 of land, contaminating soils and waters with sewage, petroleum residues, and heavy metals. The subsequent reservoir desiccation disrupted irrigation for more than 5 000 km^2 of agricultural land and reduced cooling-water availability for the Zaporizhzhia Nuclear Power Plant. Approximately 113 km^2 of forest and 3 330 km^2 of protected areas–including Ramsar wetlands and Emerald Network sites–were affected. Losses of ecosystem services are estimated at USD 8.5 billion (see Supplementary Material S3). Both the OSCE (2023) and Grygaski (2023) warn of transboundary risks from contaminated sediments and characterise the situation as a compound ecological-humanitarian emergency.

Consolidated estimates from UNEP (2022), the second Rapid Damage and Needs Assessment (World Bank, the Government of Ukraine, the European Union, and the United Nations, 2023), and the KSE (KSE, 2025) report nationwide destruction worth hundreds of billions of USD. Fires and explosions at oil depots, terminals, and industrial complexes–documented by the WWF (2022), Clean Air for Ukraine (2023), Ecoaction (2022), and CEO (2023) – generated large emissions of soot and toxic pollutants, with secondary water and soil contamination from firefighting runoff (see Supplementary Material S4 for emissions estimates). Chemical accidents involving ammonia, nitric acid, and other hazardous substances have been documented by the OSCE (2023) and CEO (2023), while Grygaski's (2023) report highlights additional risks from tailings ponds and waste impoundments located in active combat zones.

Satellite observations by the European Commission's Joint Research Centre (JRC, 2025) indicate severe air-quality deterioration, deforestation, and soil erosion. Clean Air for Ukraine (2023) reports widespread forest and peatland fires; World Wide Fund for Nature (WWF, 2022) estimates that more than 30,000 km^2 of forest and 20% of protected areas have been affected. National monitoring by the State Forest Resources Agency of Ukraine (2024) confirms elevated wildfire risk in conflict-adjacent areas. These processes undermine hydrological balance, exacerbate erosion, and reduce agricultural resilience.

Environmental degradation is translating into measurable public-health risks. Evidence from the Journal of Occupational Medicine and Toxicology (Hryhorczuk et al., 2024) and OSCE (2023) shows contamination of air, water, and soil, with fine particulate matter in Kyiv reaching nearly twenty-eight times World Health Organization guidelines during intense bombardment. Satellite-based assessments (Zalakeviciute et al., 2022) confirm spikes in $PM_{2.5}$ and NO_2. Humanitarian assessments by International Organization for Migration (IOM, 2023), as well as WHO (2023) report increased respiratory symptoms in Mykolaiv, Dnipropetrovsk, and Zaporizhzhia, while soil and groundwater contamination is documented by Environment-People-Law (EPL, 2024). Repeated strikes on facilities storing ammonia, chlorine, and nitric acid create complex exposure pathways (Szklarski, 2023).

Evidence from UNEP (2022), UNEP (2023), reports authored by Grygaski and published on the UNECE website (2023), Ukrainian governmental bodies, NGOs, and peer-reviewed studies consistently indicates extensive and persistent ecosystem degradation across multiple regions of Ukraine, including soil, water, air, and biota. These findings appear consistent with commonly referenced characteristics of "widespread and long-term damage," although no fixed quantitative thresholds are applied in this study. Agricultural compaction, hydrological disruption in the Dnipro basin, and transboundary pollution illustrate how environmental

BOX 1 Key policy recommendations for environmental monitoring and recovery in war-affected Ukraine.

- *Standardise methodologies* by adopting common protocols for mapping and classifying war-related environmental damage (soil degradation, hydrological disruption, air-pollution episodes, forest loss) to enable consistent assessment across regions and over time.
- *Enhance transparency* and participation by committing to open access (subject to security constraints) to war-related environmental and geospatial datasets, enabling independent verification, scientific analysis, and informed public debate.
- *Use the geospatial typology* (industrial/energy sites, hydrological disruptions, agricultural cratering, forest/protected-area damage, urban "grey zones") to identify priority restoration zones and sequence interventions.
- *Implement risk-based zoning*, designating high-risk areas (e.g., heavily cratered cropland, contaminated floodplains, industrial hotspots) for restricted use, demining, remediation, and monitoring before normal economic activity resumes.
- *Empower communities and civil society to participate* in environmental damage reporting, and ensure that monitoring outputs are archived to evidentiary standards suitable for future assessment processes, compensation claims, or environmental accountability mechanisms.
- *Align green reconstruction with spatial evidence* by requiring national and donor-funded reconstruction plans (housing, transport, energy, agriculture) to reference mapped environmental damage, embed nature-based and low-carbon approaches, and guide dedicated environmental recovery funds towards zones of highest ecological and human risk.
- *Support longitudinal studies in the most affected areas* to track chronic impacts on health, productivity, and ecosystem resilience, and to inform adaptive policy and management over time.

damage has become systemic. Recent geospatial work by Dietrich et al. (2025) and Ge et al. (2022) further strengthens this empirical basis. The findings underscore the need for standardised assessment methodologies, accountability mechanisms, and recovery approaches aligned with European sustainability frameworks and the EU Green Deal, linking environmental restoration with security, climate adaptation, and ecological justice.

While these sources provide valuable estimates of environmental damage and economic loss, the integration of spatially explicit geospatial analysis with valuation frameworks remains limited. Bridging this gap represents an important direction for future research, particularly in linking observed environmental change to compensation mechanisms and restoration financing. Overall, qualitative and institutional evidence supports the patterns observed in geospatial data, although differences in methodologies, reporting standards, and spatial coverage introduce uncertainty.

3.4 Implications for research and policy

From a methodological perspective, the combined use of geospatial analysis and qualitative evidence highlights several priorities for further research. In particular, improving the robustness of conflict-environment assessments will require the development of hybrid monitoring approaches that systematically integrate remote sensing with targeted field-based validation in accessible areas. Moreover, expanding temporal coverage through longitudinal data collection could capture delayed and cumulative ecosystem impacts that are not detectable through short-term observation windows. In addition, greater standardisation of data collection and classification protocols across institutions could enhance comparability and reduce fragmentation in monitoring efforts. Finally, closer integration of environmental and public health data represents a critical next step to better understand exposure pathways and long-term risks for affected populations. Considered together, these priorities provide a methodological pathway for strengthening future assessments of war-related environmental damage. This distinction is particularly relevant when aligning geospatial evidence with formal environmental damage assessment frameworks, where the identification of disturbance represents only the first step toward establishing ecological injury and liability. At the same time, strengthening the policy relevance of such assessments requires closer integration with established environmental damage frameworks. In particular, linking geospatial indicators of disturbance with ecosystem service assessment, baseline reconstruction, and recovery trajectories would enable a more complete evaluation of environmental damage in line with NRDA and ELD approaches.

In addition, alignment with large-scale assessment initiatives, such as the World Bank Rapid Damage and Needs Assessment, could enhance the applicability of spatial data for prioritising investments, designing restoration programmes, and informing compensation and liability processes.

Beyond methodological improvements, the findings also point to urgent policy implications. War-related environmental damage in Ukraine is both systemic and long-lasting, while monitoring and recovery efforts remain highly fragmented. Building on the geospatial typology and multi-source evidence presented above, Box 1 outlines a set of priority policy measures to support environmental monitoring and advance green recovery.

However, the implementation of these measures will require integration with quantitative assessment frameworks, including ecosystem service valuation, cost estimation, and scaling approaches for restoration interventions. Taken together, these recommendations provide a structured basis for integrating environmental monitoring, risk assessment, and adaptive recovery planning in conflict-affected regions. However, their implementation depends on data availability, institutional capacity, and security constraints, which continue to limit access and coordination. Strengthening transparency and enabling the involvement of scientific institutions and civil society may improve data quality and accountability, while balancing the protection of sensitive information. The findings also highlight the need to align environmental recovery with broader reconstruction and sustainability agendas, although uncertainties regarding the scale and persistence of impacts require adaptive, evidence-based approaches. The linkage between observed environmental damage and the concept of ecocide should therefore be understood as an analytical interpretation supported by available evidence, rather than as a definitive or legally binding classification. Overall, the results contribute to ongoing discussions on the assessment of large-scale environmental harm in conflict settings, while emphasising the need for further methodological and empirical development.

4 Conclusion

The case study of Russia's invasion of Ukraine and the ongoing military conflict between the two countries has revealed the occurrence of extensive environmental destruction across various ecosystems in the region. Geospatial analysis, combined with other data, reveals widespread, long-lasting damage consistent with "severe, widespread and long-term" environmental harm, providing a basis for ecocide discussions in regions where international military conflicts occur. While linked to conflict, some environmental changes may have pre-existing causes. The study identifies conflict-associated environmental change, distinguishing scientific assessment from legal definitions of ecocide. This original framework integrates geospatial analysis, satellite data, and qualitative evidence to assess conflict-environment impacts. It offers a reproducible approach for diagnosing wartime ecosystem damage, applicable to other conflicts with reliable data and governance capacity. Limitations include data gaps in combat zones and unfolding long-term consequences. The study contributes a structured analysis of environmental disturbances in Ukraine, informing future ecological, legal, and policy analyses. Future research should prioritize strengthening monitoring systems, integrating remote sensing with ground validation, developing standardized indicators, and conducting interdisciplinary research to translate observations into actionable impact assessments and recovery plans.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

WL: Methodology, Conceptualization, Writing – original draft, Validation, Writing – review and editing, Formal Analysis, Supervision. MF: Writing – original draft, Conceptualization, Validation, Writing – review and editing, Supervision. OK: Methodology, Validation, Formal Analysis, Data curation, Conceptualization, Software, Writing – review and editing, Resources, Writing – original draft, Visualization. US: Visualization, Conceptualization, Writing – original draft, Resources, Validation, Writing – review and editing, Formal Analysis, Data curation, Methodology. NY: Conceptualization, Writing – original draft, Resources, Investigation, Writing – review and editing, Formal Analysis, Validation, Methodology. MR: Visualization, Formal Analysis, Validation, Resources, Methodology, Conceptualization, Writing – original draft, Investigation, Writing – review and editing. JE: Writing – original draft, Validation, Writing – review and editing, Conceptualization. MD: Conceptualization, Methodology, Validation, Formal Analysis, Resources, Data curation, Writing – review and editing, Writing – original draft. JL: Data curation, Validation, Visualization, Formal Analysis, Conceptualization, Writing – review and editing, Supervision, Writing – original draft.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgements

The authors acknowledge the support of the German Federal Environmental Foundation (DBU) through the project 'Ukraine Nature Network', a platform for the documentation and dissemination of information on environmental and nature conservation initiatives in Ukraine in the context of the war. This work acknowledges the support of the Foundation for Science and Technology (FCT), within the framework of the UID/04292/2025, Marine and Environmental Sciences Centre (MARE), https://doi.org/10.54499/UID/04292/2025 and the framework of the LA/P/0069/2020, Associate Laboratory ARNET, https://doi.org/10.54499/LA/P/0069/2020.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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