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War in Ukraine: an overview of environmental impacts and consequences for human health

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This paper discusses the significant yet often neglected environmental repercussions of the Russian invasion of Ukraine, highlighting the adverse effects on soil, air, water, and biodiversity. Through a comprehensive bibliometric analysis, it examined existing research on the environmental impact of wars, focusing on key dimensions such as water, air, soil, and biodiversity. The study further explores various methods as well as sustainable-oriented solutions aimed at mitigating these effects on the environment. Furthermore, it discusses the immediate and long-term challenges Ukraine faces in its recovery efforts, emphasizing the need for environmentally conscious approaches to address the many environmental problems caused by the war issues. In the end, the paper presents findings from a workshop involving 15 Ukrainian experts from three different Ukrainian universities, which aimed to understand the broader implications of environmental damages to human health. This interdisciplinary approach offers valuable insights into the intersection of environmental degradation and public health, proposing operational strategies for recovery and sustainability in post-conflict settings.

KEYWORDS

environmental impacts, military drivers, Russian-Ukrainian war, nature-friendly solutions, human health

1 Introduction

The Russian invasion of Ukraine poses great challenges for world peace and to wellbeing of many people, especially at a time when environmental problems and global issues such as climate change call for integrated action among all countries (Kuzemko et al., 2022). The environmental impacts of the war in Ukraine include the release of toxic materials into the air, water and soil from explosions, combustion, fires, military waste, construction of bunkers, and heavy military machinery. Wartime environmental degradation is spread across hundreds of square kilometers.

The environment is typically under-prioritized during conflicts, particularly in the face of so much human suffering. However, both human rights and ecosystems depend on a healthy environment (United Nations, 2021). Moreover, having access to clean water, air, soil, and biodiversity, as well as access to ecosystem services, would be one of the most important conditions for displaced people to come back to Ukraine (see Pereira et al., 2022).

Russia's war against Ukraine has already affected 20% of protected areas in Ukraine, where Russian army occupied eight nature reserves and 10 national parks, posing risk to important wildlife sites. This includes: 2.9 million hectares of the Emerald Network are at risk (Pereira et al., 2022; Wetlands International Europe, 2022; European Wilderness Society, 2023). These territories are a significant part of the nature conservation network of Europe, which is protected within the framework of EU and Council of Europe legislations. 16 Ramsar sites with an area of more than 600,000 hectares are under threat of destruction (RAMSAR, 2022). These are the territories that have the status of wetlands of international importance due to their unique biodiversity. The Great and Small Kuchugury Archipelago with an area of 7,740 ha is now liberated, but due to its proximity to the front line, it is still under threat (RAMSAR, 2022).

The impacts of the war on the environment should be carefully studied and analyzed in order to recover damaged and polluted ecosystems (Westing, 2008; Certini et al., 2013). Figure 1 illustrates how military drivers could endanger several dimensions of the environment, such as water, air, biodiversity, and soil.

On 21 September, Ukraine's Supreme Council adopted Bill 7475 in its first reading. The bill is intended to strengthen protection of Ukraine's state borders, but content-wise, it is primarily devoted to procedures for removing land from Nature Reserve Fund of Ukraine (2024). Infrastructure support for the border zone requires significant intervention in ecosystems: building defense structures, infrastructure, and roads, draining swamps, and expanding clearcutting in forests. Thus, any hardening of the border undoubtedly results in impacts on natural ecosystems (Wetlands International Europe, 2022; European Wilderness Society, 2023).

In this context, the goal of this paper is 3-fold. Firstly, this paper aims to identify, through a bibliometric assessment, the environmental drivers that could impact the environment and understand how these military drivers can impose environmental damages to the Ukrainian protected areas, especially to the dimensions related to water, air, biodiversity and soil. Secondly, the authors discuss what the literature brings as the main methods that could be used to identify the environmental impacts of the war in Ukraine as well as the possible Nature-Friendly solutions that could be used to recover the environment, especially the Ukrainian protected areas. Finally, since this is also a health-related topic, this paper also explored the direct and indirect impacts of the war to human health, discussing the results from a workshop promoted by the Ukraine Nature Project with 15 Ukrainian experts belonging to three different Ukrainian universities.

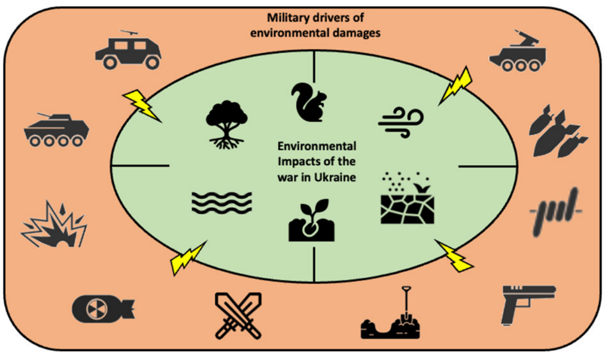

FIGURE 1
Environmental impacts of the war in Ukraine. Source: developed by the authors.

2 Methods

To achieve the goals proposed in this study, the authors adopted a bibliometric analysis to understand the landscape of what are the military drivers are and how they impact several dimensions of the environment (Figure 2). In a second stage, the authors promoted a workshop with 15 Ukrainian experts who explored how the damage on environment could impact human's health in a direct and indirect way.

The decision to utilize bibliometric analysis based on the co-occurrence of terms in this paper is primarily driven by the need to systematically map the complex landscape of environmental impacts arising from the wars and conflicts. This analytical method allows for the identification and visualization of key research themes and the relationships between them by examining the frequency and patterns of term usage within a large corpus of academic literature (Waltman and van Eck, 2013; van Eck and Waltman, 2014; Perianes-Rodriguez et al., 2016; VOSviewer, 2024). By employing bibliometric analysis based on the co-occurence technique, the paper aims to unveil the predominant themes in existing research related to the environmental dimensions of water, air, soil, and biodiversity that are most affected by military actions. This approach not only highlights the prevalent research areas but also identifies less explored avenues that require further investigation (Leal Filho et al., 2022; Eustachio et al., 2023), thereby supporting a comprehensive understanding of the environmental consequences of the conflict and guiding future research efforts.

The selection of 15 Ukrainian experts, in turn, was influenced by several strategic considerations. First, these experts have a profound understanding of life sciences which is essential for assessing the environmental and health impacts highlighted in the paper. Their expertise ensures that the analysis is grounded in robust scientific knowledge and is capable of bridging complex environmental issues with human health outcomes. Second, their familiarity with the Ukrainian conflict context provides invaluable insights into the local environmental challenges and the specific impacts of military actions in the region. This local expertise is critical in tailoring research findings and recommendations that are contextually relevant and actionable. Third, the convenience sample of experts attending a project conference in Hamburg presents a practical opportunity to gather a diverse array of specialists from different Ukrainian universities at one time. This setting not only facilitates the direct exchange of ideas and collaboration but also enriches the research with a variety of perspectives, thereby enhancing the depth and applicability of the study findings to the Ukrainian situation.

To conduct the bibliometric analysis, the authors were inspired by previous studies (Leal Filho et al., 2022; Eustachio et al., 2023), and created one search string for each one of the environmental

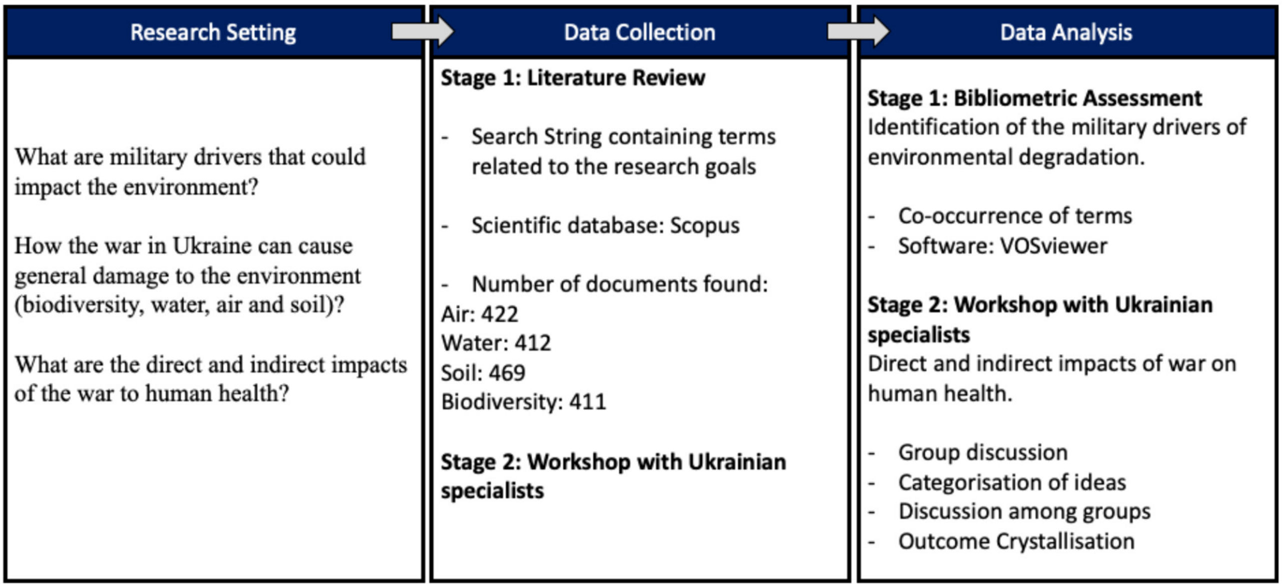

FIGURE 2
Methodological decisions. Source: developed by the authors.

dimensions: environment, soil, water and air (Appendix Table A1). Each one of the search strings was built in order to capture what the literature has been discussing on the impact of the wars and conflicts in several contexts on the environment.

In order to perform the data analysis, the authors adopted the VOSviewer (2024) software, where the selected peer-reviewed documents were used to perform the bibliometric technique co-occurrence of terms. The results are presented by a network graph, also presented in the Appendix Figures A1–A4. The diameter of the bubbles indicates the frequency of the occurrence of a specific term, while the link width indicates the strength of the connection between two terms. The terms that appear close to each other are expected to be associated, generating a thematic cluster due to their co-occurrence frequency (Waltman and van Eck, 2013; van Eck and Waltman, 2014; Perianes-Rodriguez et al., 2016; VOSviewer, 2024).

The choice to analyze the dimensions of water, air, soil, and biodiversity under the concept of the environment in this study is rooted in their fundamental significance to the ecological and human health systems (Smith et al., 2013). These elements represent critical components of the environment that sustain life and underpin the wellbeing of ecosystems and human communities. For example, water and air are essential for all biological processes, influencing public health, agricultural productivity, and climate regulation. Soil not only supports plant growth and biodiversity but also acts as a filter for pollutants, playing a pivotal role in nutrient cycling and storage. Biodiversity, in turn, encompassing the variety of all biological forms, contributes to ecosystem resilience, agricultural sustainability, and genetic resources. Examining these dimensions allows us for a comprehensive understanding of the multifaceted impacts of conflict on environmental integrity. By assessing these interconnected elements, the research aims to encapsulate the complex interplay between human activity (military actions) and the natural world, thereby informing strategies for environmental preservation and rehabilitation in conflict-affected areas.

The summary of the results were presented in the Tables 1, 2 "Military drivers and environmental impacts according to different dimensions" and "Summary of Methods to Identify the Environmental Impacts of the war in Ukraine." In a broad sense, they information about military drivers of environmental degradation, impacts and methods and techniques of assessment according to four different dimensions: soil, water, air and biodiversity.

Finally, the authors conducted a workshop in the helm of the project "Ukraine Nature" (https://www.haw-hamburg.de/forschung/forschungsprojekte-detail/project/project/show/ukraine-nature/), with 15 Ukrainian teachers and professors from Ukrainian universities (Ivano-Frankivsk National Medical University, National Forestry University of Ukraine, and the Ivan Franko National University of Lviv). The workshop was held in Hamburg on 25.08.2022, and the summary of the results of this workshop is presented in Table 3, which enriched the results from the bibliometric analysis with interdisciplinary expert knowledge, connecting with the Ukrainian context.

The refered workshop provided a platform for these experts to discuss and explicitly identify and discuss the primary environmental impacts of the war in Ukraine, such as soil degradation, water and air pollution, and biodiversity loss. Their firsthand experiences and professional expertise offered a nuanced understanding of how these environmental dimensions have been altered by military activities. Secondly, the workshop facilitated a critical examination of the potential human health ramifications stemming from these environmental impacts. Finally, the participants explored various health issues that could arise, including respiratory ailments from polluted air, waterborne diseases from contaminated water supplies, and food security problems due to compromised soil and agricultural disruption. The results are presented presented in the Appendix Table A2. This discussion was pivotal in linking environmental damage directly to public health outcomes, a connection that is often understood but not comprehensively documented with local expert testimony.

The collected data and insights from this workshop were synthesized, confirmed with the literature evidencing the impact on human health and presented in Table 3 of the study, enriching the initial findings from the bibliometric analysis. This integration of interdisciplinary expert knowledge tailored specifically to the Ukrainian context provided a richer, more contextualized view of the environmental and health landscapes during ongoing conflicts. It also underscored the unique contributions of localized expertise in crafting responses that are both scientifically informed and culturally relevant, thereby enhancing the study's applicability and impact on policy and practice in war-affected regions.

3 Results and discussion

The main results of this study are presented in Tables 1–3, which are intricately interconnected, serving to present a comprehensive view of the environmental impacts of war and the methodologies employed to address these impacts.

Table 1 details the specific environmental dimensions affected by military activities, such as soil, air, water, and biodiversity, and outlines the associated military drivers that exacerbate these impacts, such as the use of explosives and military vehicles. It lays the groundwork by systematically categorizing the various ways in which these activities contribute to environmental degradation. Building on this foundational knowledge, Table 2 in turn, explores the array of methods used to identify and assess these environmental impacts. This includes technologies and techniques ranging from remote sensing to chemical analyses, which help in detecting and quantifying the extent of damage as detailed in Table 1. Additionally, Table 2 proposes nature-friendly solutions aimed at mitigating the damage and restoring the ecological balance, thereby directly responding to the challenges highlighted in Table 1.

Table 3 extends the analyses by Tables 1, 2, by focusing on the human health implications of the environmental impacts discussed earlier. While Table 1 outlines the specific environmental dimensions affected by military activities and Table 2 details the methods to identify these impacts along with possible mitigation solutions, Table 3 shifts the focus toward the human aspect, examining how these environmental changes influence public health. The following subsections 3.1, 3.2, and 3.3 bring a discussion of the main findings.

3.1 Military drivers and environmental impacts according to different dimensions

In the elucidation of the complex interplay between military activities and environmental degradation (Lawrence and Schaefer, 2015; Broomandi et al., 2020; Chang et al., 2023; Konuk et al., 2023), Table 1 provides a comprehensive overview of the various military drivers and their corresponding impacts across different environmental dimensions: soil, air, water, and biodiversity (Pereira et al., 2022).

The table categorizes a wide range of military operations, such as the use of bombs, explosives, and missiles, the operation of military vehicles, and the execution of chemical and atomic warfare, among others (Shukla et al., 2023; Bun et al., 2024). It systematically aligns these activities with their specific environmental consequences. For instance, the detonation of explosives not only results in soil compaction and reduced water absorption capacity but also contributes to air pollution through the release of harmful gases and particles (Giri et al., 2023; Gutierrez-Carazo et al., 2023). Similarly, the intensive use of military vehicles is linked to the increased release of toxic elements and greenhouse gases, exacerbating soil and air pollution, respectively (Gutierrez-Carazo et al., 2023; Amanambu and Nduka, 2024; Ganguly et al., 2024).

The table further illustrates how these military actions lead to water pollution through contamination of aquifers and water bodies and highlights the severe impact on biodiversity, including the loss of habitat, forced animal migration, and the disruption of ecosystems (Chowdhury et al., 2023; Faseyi et al., 2023; Grimes et al., 2023; Hashimy, 2023). In this sense, these interconnections, serves as a critical tool in understanding the multifaceted environmental repercussions of military activities, underscoring the need for integrated approaches to mitigate these impacts in conflict and post-conflict scenarios.

The detonation of bombs, missiles, and other explosives in military operations significantly alters the soil structure and composition. Such activities not only lead to direct contamination from the explosives themselves but also result in undetonated ordnance remaining in the soil, posing a persistent risk (Tuzhyk and Тужик, 2023; Petrushka et al., 2024). Experimental data obtained in Lviv (Ukraine) from four explosion sites showed the concentrations of potentially hazardous elements (PTEs) such as zinc (Zn) 48–124 mg/kg, copper (Cu) 18–116 mg/kg, lead (Pb) 15–35 mg/kg, chromium (Cr) 33–36 mg/kg, nickel (Ni) 8–27 mg/kg, and cadmium (Cd) 0.5–2 mg/kg and some of them are up to 5 times higher in comparison with the standard of the permissible content. It was confirmed that the excess of these elements hampers plant growth by around 5–10% The environmental Cu risk index reached 58.2. when Cu in concentration above 3.0 mg/kg is highly toxic and can cause tissue damage, changes in root cell elongation, alterations in membrane permeability, and inhibition of electron transfer during photosynthesis (Petrushka et al., 2024). Moreover, the construction of trenches and bunkers, coupled with the intense circulation of heavy military vehicles, compresses and compacts the soil, diminishing its water absorption capacity and leading to erosion (Lindemann, 2023). The heavy use of military machinery, often dependent on oil, releases a range of toxic elements like Persistent Organic Pollutants (POPs) and Polycyclic Aromatic Hydrocarbons (PAHs) into the soil, thereby causing soil degradation and loss of agricultural productivity (Etherington, 2023; Konuk et al., 2023; Mahire et al., 2023). These pollutants disrupt soil microbiology, adversely affecting microflora and microorganisms, and lead to a reduction in the bioavailability

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TABLE 1 Military drivers and environmental impacts according to different dimensions.

Military drivers of environmental degradation	Soil	Air	Water	Biodiversity
Bombs, explosives detonation, artillery, drones, and military aviation	Soil Compression/compaction, reduced water absorption capacity Loss of nutrients and mineral composition Loss of microorganisms' activity Soil fauna and flora degradation Reduction of bioavailability Acute toxicity: soil contamination, pollution of aquifers and underground/groundwater Soil Erosion Soil acidity Soil degradation	Air pollutants (gases): ammonia, carbon monoxide, sulfur dioxide, nitrous oxides, methane, carbon dioxide and chlorofluorocarbons etc. Particle pollution: dust, dirt, soot, or smoke Greenhouse gases production Atmospheric pollution Atmospheric thermodynamics alteration Ozone depletion Transborder pollution	Chemical pollution/contamination: aquifers, drinking and freshwater, rivers, sea, groundwater, wetlands, surface water, estuaries Acid rain Water alkalinity change	Habitat degradation Loss of biodiversity Animal welfare Forced animal migration Fauna and flora contamination Aquatic species pollution Food contamination Microbiome compromise Neurotoxicity of animals Reduction of the number of species and continuous impacts on other animals.
Unexploded ordnance or mines	Acute toxicity: soil contamination, pollution of aquifers and underground/groundwater		Pollution/contamination: aquifers, drinking and freshwater, rivers, sea, groundwater, wetlands, surface water, and estuaries	Fauna and flora contamination Habitat degradation Food contamination Microbiome compromise Animal welfare
Fires caused by explosions, missile attacks and intentional arson	Soil Erosion Loss of microorganisms' activity Soil fauna and flora degradation Reduction of bioavailability Change in acid-alkaline conditions toward a neutral pH reaction	Particle pollution: dust, dirt, soot, or smoke Products of combustions Transborder pollution Greenhouse gases production, Atmospheric pollution, atmospheric thermodynamics alteration Ozone depletion Transborder pollution	Water overconsumption for firefighting.	Habitat degradation Loss of biodiversity Shortage of animal food Deforestation Vegetation cover degradation Reduction of the number of species and continuous impacts on other animals
Occupation; military vehicles (cars, tanks, personnel carriers, combat support vehicles, etc.), lead to oil spills, increasing the release of toxic elements to soil, water and air (intense circulation of heavy military vehicles)	Acute toxicity: soil contamination, pollution of aquifers and underground/groundwater Soil Compression/compaction, reduced water absorption capacity Loss of nutrients and mineral composition Loss of microorganisms' activity Soil fauna and flora degradation Reduction of bioavailability	Air pollutants (gases): ammonia, carbon monoxide, sulfur dioxide, nitrous oxides, methane, carbon dioxide and chlorofluorocarbons etc.	Toxic and oil pollution	Habitat degradation Fauna and flora contamination Forced animal migration Animal diseases Reduction of the number of species and continuous impacts on other animals.
Military waste	Acute toxicity: soil contamination, pollution of aquifers and underground/groundwater		Pollution/contamination: aquifers, drinking and freshwater, rivers, sea, groundwater, wetlands, surface water, estuaries	Food contamination Animal diseases
Atomic warfare, radioactive particles	Radiation exposure/radioactive contamination	Possible radioactive pollution	Radioactive pollution/contamination	Radiation poisoning (animals and plants)
Armed clashes: gun fires, construction of tranches and bunkers, flooding as a weapon	Biological pollution (microbes, viruses) Soil Erosion		Biological Pollution (microbes, viruses) Sewage	Habitat degradation Loss of biodiversity Forced animal migration Animal diseases Aquatic species pollution Animal welfare Vegetation cover degradation

of nutrients, further exacerbating the ecological impact (Rashid et al., 2023; Zeb et al., 2024).

Air quality is profoundly affected by military activities. The use of vehicles, aircraft, drones, and the burning of fossil fuels in military logistics significantly increase the emission of greenhouse gases and other pollutants such as ammonia, carbon monoxide, sulfur dioxide, and nitrous oxides. Furthermore, the particulate pollution resulting from explosions, artillery fire, and the burning of infrastructure facilities adds to the atmospheric burden of pollutants like sulfuric acid, ammonium sulfate, and smoke. During the 1st months of the Russian war against Ukraine concentrations of $PM_{2.5}$ (particulate matter with aerodynamic diameter ≤ 2.5 μm) drastically increased: peak concentrations of 24.2 $\mu g\ m^{-3}$ which is significantly above the WHO's recommended safe levels for 24-h exposure (15 $\mu g\ m^{-3}$). It correlated the most with war activities as well as NO_2 (max: 139.7 $\mu mol\ m^{-2}$) concentrations over 500 $\mu mol\ m^{-2}$ are a health concern. At the same time CO and O_3 levels increased, while SO_2 concentrations reduced 4-fold as war intensified (Zalakeviciute et al., 2022). This atmospheric pollution alters atmospheric thermodynamics and contributes to broader issues such as climate change, ozone depletion, acid rain, and transborder pollution (Pereira et al., 2022; da Costa et al., 2023; Piehler and Grant, 2023; Ganguly et al., 2024).

Water bodies suffer extensively due to military operations. Explosions and military waste contaminate aquifers, rivers, seas, and groundwater with heavy metals, oil, and other harmful substances (Mensah and Tuokuu, 2023). The destruction of water supply infrastructure, such as dams and sewage systems, coupled with overconsumption of water for firefighting, exacerbates the scarcity of water resources. Furthermore, the contamination of water by military wastes, including chemical, radioactive, and biological substances, poses severe threats to water quality, making it unsafe for human consumption and aquatic life (Kitowski et al., 2023; Mardones, 2023).

Biodiversity is another victim of military operations (Antoniuk, 2023). The destruction of habitats through deforestation, wildfires, and explosions leads to a loss of biodiversity and irreversible migration of species populations (Lawrence and Schaefer, 2015; Pereira et al., 2022; Rawtani et al., 2022; Grimes et al., 2023; Ntui, 2023). Fauna and flora are contaminated by pollutants, which can lead to diseases, food shortages, and even neurotoxicity in both animals and humans (Grimes et al., 2023). Radiation exposure from atomic warfare poses a significant threat to all forms of life, leading to genetic mutations and a reduction in the number of species. Moreover, the degradation of protected areas and vegetation cover due to military activities further impacts the ecological balance (Rawtani et al., 2022; Gallo-Cajiao et al., 2023).

In sum, military activities have multifaceted environmental impacts, significantly degrading soil, air, water quality, and biodiversity. The persistence of these impacts poses a continuous threat to the environment, necessitating a reevaluation of military practices and the implementation of strategies to mitigate these detrimental effects. Understanding and addressing these environmental consequences are essential for preserving the ecological integrity and ensuring the sustainability of our planet.

3.2 Environmental impact identification methods and sustainable solutions

In the context of the War in Ukraine, the environmental impact has been profound, spanning across dimensions of soil, water, air, and biodiversity (Pereira et al., 2022). Understanding these impacts through various identification methods and implementing nature-friendly solutions is vital for ecological recovery (Sangwan and Dukare, 2018; Tiwari et al., 2019; Niyogi et al., 2023).

In the soil dimension, the presence of land mines and military operations has significantly altered soil characteristics. Electromagnetic techniques, ground penetrating radar, and nuclear quadrupole resonance/neutron probes have been pivotal in identifying these changes. These technologies, alongside semi-quantitative field surveys supported by laboratory analyses of soil samples, offer comprehensive insight into the extent of soil damage. In response, methods like manual demining, utilization of mine detection dogs, biodetection techniques, drones, robotics, and controlled detonation are being employed (Williams, 1995; Newman and Mercer, 2000; Won et al., 2001; Chiovelli et al., 2018). Additionally, for military waste and contamination, crowdsourced data has been instrumental in pinpointing the type and location of waste (Williams, 2013; Weir et al., 2019; Broomandi et al., 2020). This information, along with expert analysis and toxicological soil analysis, forms the basis for bioremediation, phytostabilization, mycoremediation, and other restoration practices like electrokinetic and thermal desorption, soil washing, and ecological restoration (Rhodes, 2013; Mishra and Venkateswara Sarma, 2017; García-Sánchez et al., 2018).

The water dimension has also been critically impacted, with issues like acid rain, pH alteration in rivers and groundwater, and pollution from heavy metals and oil. To address these, pH measurement, chemical analysis of water and soil samples, and biological monitoring are employed (Mensah and Tuokuu, 2023; Strokal et al., 2023). Remote sensing and satellite imagery provide a broader perspective on the extent of water body alteration. In tackling these issues, buffering affected waters, establishing water treatment facilities, implementing policies and legislation, and restoring damaged ecosystems are key (Sawaya et al., 2003; see. Ritchie et al., 2003; Vignolo et al., 2006; Schaeffer et al., 2013). Furthermore, bioremediation, phytoremediation, sediment removal, oil spill containment, and cleanup techniques are crucial in addressing contamination in aquifers, rivers, seas, groundwater, wetlands, surface water, and estuaries (Macaulay and Rees, 2014; Arora, 2018; Bhandari et al., 2023; Sinam et al., 2024).

Air quality has deteriorated due to wildfires, heavy military vehicle circulation, and explosions (Mehrabi et al., 2023). Methods like air particle measurement, chemical analysis, computational fluid dynamics, and computer simulation are used to assess air quality and estimate pollutants. To mitigate these impacts, establishing firebreaks, reforesting with fire-resistant species, and undertaking carbon sequestration projects are essential (Mehrabi et al., 2023).

Biodiversity loss, a critical concern, is evaluated through chemical analysis, computer modeling, field surveys, and remote sensing (Lawrence and Schaefer, 2015; Pereira et al., 2022; Rawtani et al., 2022; Grimes et al., 2023; Ntui, 2023). Efforts in habitat

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TABLE 2 Summary of methods to identify the environmental impacts of the war in Ukraine.

Dimension	Military drivers	Possible methods to identify the impacts		Possible nature-friendly solutions	
Soil	Unexploded ordnance or mines	Military operations Electromagnetic techniques Grounding penetrating radar Nuclear quadrupole resonance/neutron probes	Damage assessment (Semi-quantitative field survey supported by laboratory analyses of soil samples)	Manual Demining Mine detection dogs. Bio detection techniques	Drones and Robotics Ground Penetrating Radar (GPR) Controlled Detonation
	Military waste	Crowdsourcing data informing the type of military waste and its location (photos, survey, qualitative description)	Experts' involvement in understanding the type of military waste and its environmental consequences. Toxicological soil analysis Biodiversity soil analysis	Bioremediation Phytostabilization Mycoremediation Constructed Wetlands Biochar Application Nanoremediation Electrokinetic Remediation Thermal Desorption	Electrokinetic Remediation Thermal Desorption Soil Washing Radiation Shielding and Ecological Restoration Sustainable Policy and Practice Implementation
	Bombs, explosives detonation, artillery, drones, military aviation Armed clashes: construction of tranches and bunkers, flooding as a weapon	Crowdsourcing data can inform the changes in the land surface (photos, survey, and qualitative description).	Satellite imagery Expert analysis of the soil.	Reforestation and Afforestation Erosion Control Measures Soil Decompaction Wetland Restoration	Creating Buffer Zones Permaculture and Sustainable Land Use Practices Remediation of Trenches and Bunkers Use of Native Plant Species
Air	Bombs, explosives detonation, artillery, drones, military aviation Fires caused by explosions, missile attacks and intentional arson Occupation; military vehicles (intense circulation of heavy military vehicles)	Measurement of air particles Air Analysis Calculations, indexes Chemical analysis Computational fluid dynamics Computer simulation Speculation and projection	Concentration analysis Electronic guidance system Environmental monitoring Explosion testing High-speed photography	Firebreaks Reforestation and Afforestation with Fire-Resistant Species	Restoration of Burned Areas Carbon Sequestration Projects
Biodiversity	Bombs, explosives detonation, artillery, drones, and military aviation Fires caused by explosions, missile attacks, and intentional arson Unexploded ordnance or mines	Chemical analysis Computer modeling Concentration analysis Damage detection Field pictures Ecological risk assessment Ecotoxicity Environmental monitoring Surveying wildlife	Ecological surveys and habitat assessment Remote sensing Risk Analysis/Assessment Toxicity testing Vegetation assessment Data about national biocapacity extracted from the Global Footprint Network.	Habitat Restoration and Conservation Ecosystem-Based Management	Pollution Cleanup and Prevention Restoring Soil Health Crisis Response Plans for Wildlife
Water	Bombs, explosives detonation, artillery, drones, and military aviation	Water Sampling and Chemical Analysis Sediment Analysis Biological Monitoring Remote Sensing and Aerial Photography	Modeling and simulation Hydrological studies pH measurement Biomarkers and Bioassays Trace Metal Speciation Isotope Analysis	Bioremediation Phytoremediation Sediment Removal Oil spill containment and cleanup	Buffering Affected Waters Water Treatment Facilities Water Filtration Systems Aeration Restoration of Aquatic Habitats
	Armed clashes: gun fires, construction of tranches and bunkers, flooding as a weapon: (pollution sewage from household latrines, fuel and lubricants from petrol stations, heavy metals and PAHs)	Water quality testing Sediment analysis Remote sensing and GIS Mapping Biological Monitoring	Health risk assessments Ecotoxicological assessments Drone surveillance Isotope Tracing	Floodplain Restoration Vegetative Buffer Zones	Improved sewage and waste management Erosion control Bioremediation

restoration, ecosystem-based management, pollution cleanup, and soil health restoration are underway to conserve biodiversity (Gallo-Cajiao et al., 2023).

These multifaceted environmental impacts of the war in Ukraine require a holistic approach combining advanced technological methods and nature-friendly solutions. The collaboration of scientists, environmentalists, policy-makers, and local communities is crucial in this endeavor, ensuring a sustainable recovery, conservation of the Ukrainian environment post-conflict and guaranteeing human health, as discussed in the following section.

3.3 Consequences of environmental impacts to human health

A workshop with Ukrainian professors was held to enrich the results with interdisciplinary expert knowledge and narrow it down to the Ukrainian context. The workshop, which involved 15 professors from 3 Ukrainian universities (Ivano-Frankivsk National Medical University, National Forestry University of Ukraine, and the Ivan Franko National University of Lviv), was held in Hamburg on 25.08.2022. As a result, the project team formed answers into the table considering four dimensions (water, soil, biodiversity, and air) and exploring the consequences and impacts to public/human health.

The war in Ukraine has illuminated the profound and multifaceted impact of conflict on environmental health and, subsequently, human health. The interplay of water, air, soil, and biodiversity within this war context has led to a cascade of health issues, which require comprehensive understanding and action (Khorram-Manesh et al., 2023; Ntui, 2023; Rashid et al., 2023).

The issues related to water in the war zone are multifarious. The risk of floods and desertification, exacerbated by climate change and environmental mismanagement, presents significant challenges. Flooding can contaminate water sources, leading to the spread of waterborne diseases, while desertification reduces water availability, contributing to dehydration and food scarcity (Shumilova et al., 2023). The scarcity of drinking water or food can lead to exhaustion and dehydration, severely impacting cognitive and physical abilities, crucial for survival in conflict situations. Furthermore, the destruction of settlements in war zones disrupts access to clean water and sanitation facilities, exacerbating the deterioration of hygiene conditions and increasing the risk of infectious diseases (Topluoglu et al., 2023). These conditions often lead to a high death rate, particularly among vulnerable populations like children and the elderly. Moreover, the lack of reliable information on water quality in these areas hampers effective responses to waterborne diseases and poses additional health risks (Spiegel et al., 2023).

The air quality in war zones is also a critical concern (Hook and Marcantonio, 2023; Warsame et al., 2023). The toxic effects on respiratory and skin health due to exposure to pollutants can cause various health issues, including respiratory problems, skin irritations, and in severe cases, life-threatening conditions like pulmonary edema. The damage caused by these pollutants extends to multiple body systems, including the respiratory, digestive, reproductive, circulatory, excretory, and nervous systems, leading to a broad spectrum of health problems. Long-term exposure to certain chemicals and toxins in the air can trigger allergic reactions, increase the risk of cancer, and cause both acute and chronic health effects, which place a significant burden on the already strained healthcare systems in war-torn areas (Sharma et al., 2023; Shetty et al., 2023; see Pat et al., 2023).

Soil pollution in the context of war leads to reduced crop yields, resulting in food shortages and subsequent malnutrition (Leal Filho et al., 2023). This weakens the immune system, making individuals more susceptible to diseases and long-term health issues, including stunted growth and developmental delays in children. Soil pollution also contaminates groundwater and surface water, leading to a wide range of health problems, from gastrointestinal diseases to chronic health conditions like kidney damage and increased cancer risk. Moreover, polluted soil can be a breeding ground for harmful pathogens, increasing the risk of soil-transmitted infections, which can exacerbate other health conditions and contribute to a compounded health impact (Antoniuk, 2023).

Biodiversity loss due to war significantly impacts human health. Exposure to chemical or biological agents can cause poisoning and burns, leading to acute and chronic health issues (Lawrence and Schaefer, 2015). The loss of dietary fibers due to reduced biodiversity can result in digestive problems and chronic diseases (Johns and Eyzaguirre, 2006; Makki et al., 2018). Toxicity and intoxication from contaminated environments impact liver and kidney function and the neurological system (Vandana et al., 2022). Loud explosions in conflict zones can cause eardrum ruptures, leading to hearing impairment and chronic ear infections. Injuries such as contusions are common, leading to various complications (Myers et al., 2009). The stress and physical strain of living in a war environment can increase the risk of unintentional abortions and stress-induced mortality (Hobfoll et al., 1991). Neurological changes, both reversible and irreversible, are consequences of exposure to neurotoxic agents and the psychological trauma of war (Marshall et al., 2019). Radiation sickness, a concern in warfare involving nuclear materials, poses long-term health risks (Hyams et al., 2002). The spread of endemic diseases is exacerbated by disrupted healthcare systems and poor environmental conditions (Pereira et al., 2022).

4 Conclusions

This paper evidences that the war in Ukriane has not only inflicted profound human suffering and infrastructural damage but has also wreaked havoc on the environment, thereby exacerbating health risks in numerous ways.

Theoretically, this paper extends the understanding of environmental degradation in war contexts, emphasizing the interconnectedness of various environmental dimension such as water, air, soil, and biodiversity, and their cumulative impact on public health. It underscores the need for an integrated approach to environmental health, particularly in conflict zones, where traditional models of environmental conservation and health promotion are often inadequate.

TABLE 3 War consequences to human health.

Dimension	Environmental impacts	Explored consequences to human health	References
Soil	Acute toxicity: soil contamination, pollution of aquifers and underground/groundwater	**Threats to life and increased mortality risk:** Exposure to toxic substances in polluted soil can lead to acute poisoning, which in severe cases can be fatal. Long-term exposure to soil pollutants can increase the risk of chronic diseases and cancers, leading to a higher overall mortality rate. This is particularly concerning in war zones, where access to healthcare and disease monitoring is often limited. The combined effects of malnutrition, waterborne diseases, and increased infections due to soil pollution can significantly increase the mortality risk, especially among children, the elderly, and those with pre-existing health conditions. The presence of heavy metals, such as lead or arsenic, can lead to chronic health conditions, including kidney damage and increased risk of certain cancers.	Lenart-Boro and Boro, 2014; Steffan et al., 2017; Adeola, 2020; Okereafor et al., 2020; Alengebawy et al., 2021
	Acute toxicity: soil contamination, pollution of aquifers and underground/groundwater Soil compression/compaction, reduced water absorption capacity Loss of nutrients and mineral composition Loss of microorganisms' activity Soil fauna and flora degradation Reduction of bioavailability Erosion Radiation exposure/radioactive contamination Soil acidity Soil degradation	**Reduced crop yields and shortage of cultivated areas for farming leading to food shortages:** Soil pollution, often caused by the use of chemicals in warfare or destruction of agricultural land, leads to reduced crop yields. This results in food shortages, which can cause malnutrition and associated health problems, especially in vulnerable populations like children and the elderly. Malnutrition weakens the immune system, making individuals more susceptible to diseases, and can lead to long-term health issues in children, including stunted growth and developmental delays.	Bultman et al., 2012; Lenart-Boro and Boro, 2014; Islam and Wong, 2017; Steffan et al., 2017; Brevik et al., 2020; Manisalidis et al., 2020; Naidu, 2021
	Biological pollution (microbes, viruses)	**Increased risk of infections:** Polluted soil can be a breeding ground for harmful bacteria, viruses, and parasites. In a war context, where sanitation and hygiene might be compromised, there is an increased risk of soil-transmitted infections. These infections can range from relatively mild conditions to severe illnesses, especially in populations with limited access to healthcare. They can also exacerbate other health conditions, leading to a compounded health impact.	Bultman et al., 2012; Lenart-Boro and Boro, 2014; Bintsis, 2018; Manisalidis et al., 2020
	Radiation exposure/radioactive pollution	**Health concerns associated with radiation sickness:** In cases where warfare involves nuclear materials, radiation sickness becomes a concern, with symptoms ranging from acute radiation syndrome to long-term effects like cancer and birth defects.	Douple et al., 2013; Manisalidis et al., 2020; McClellan, 2020
Air	Air pollutants (gases): ammonia, carbon monoxide, sulfur dioxide, nitrous oxides, methane, carbon dioxide and chlorofluorocarbons Particle pollution: dust, dirt, soot, or smoke	**Toxic effects on respiratory and skin health:** Contaminated air can carry harmful chemicals and pathogens that, when ingested or contacted, cause respiratory issues, skin irritations, rashes, and dermatitis, eye irritation, and respiratory symptoms. Inhalation of vapors or aerosols from polluted air sources can lead to respiratory problems, including bronchitis, asthma, inducing new allergies and in severe cases, life-threatening conditions like pulmonary edema. Damage to Respiratory, Digestive, Reproductive Systems, Blood Circulation, Excretory **Acute and chronic health effects:** Acute health effects may include immediate symptoms like nausea, vomiting, diarrhea, and acute skin or respiratory reactions. These are often seen shortly after exposure to contaminated air Chronic health effects are the result of long-term exposure and may develop over years. They include serious conditions like cancer, chronic respiratory diseases, kidney dysfunction, and chronic liver diseases. Both acute and chronic effects significantly burden the healthcare system, especially in war-torn areas where healthcare infrastructure may already be compromised.	Schulze et al., 2017; Adeola, 2020; Manisalidis et al., 2020; Vandana et al., 2022

(Continued)

TABLE 3 (Continued)

Dimension	Environmental impacts	Explored consequences to human health	References
Biodiversity	Biodiversity loss	**Health risks linked to infectious diseases from decomposing animals:** In war zones, the decomposition of animals can be a significant health concern, as it can lead to the spread of infectious diseases, particularly in areas with poor sanitation and disrupted waste management systems. **Comprehensive adverse effects on human body systems:** Affect ecosystem services that support clean air, water, and food, leading to adverse effects on various human body systems, including respiratory, cardiovascular, and immune systems.	Schulze et al., 2017; Bintsis, 2018; Brevik et al., 2020; Zaghloul et al., 2020
	Fauna and flora contamination	**Limited access to sea fauna and flora:** Lead to the loss of crucial dietary sources, affecting nutrition. The contamination of water bodies also impacts livelihoods for communities dependent on fishing, leading to economic stress and its associated health impacts.	Zaghloul et al., 2020; Kumar et al., 2021; Vandana et al., 2022
Water	Water overconsumption Pollution/contamination: aquifers, rivers, sea, groundwater, wetlands, surface water; estuaries Biological Pollution (microbes, viruses)	**Exhaustion (dehydration):** In war zones, exhaustion and dehydration are exacerbated by limited access to clean water, with polluted water sources posing additional health risks. Dehydration affects cognitive and physical abilities, crucial for survival in conflict situations. **Deterioration of hygiene conditions:** With limited access to clean water, maintaining hygiene becomes challenging, increasing the risk of skin diseases, gastrointestinal infections, and other hygiene-related illnesses. Inadequate sanitation facilities further compound these risks, particularly in refugee camps or temporary shelters. War can disrupt healthcare systems and sanitation, leading to the spread of endemic diseases. Poor environmental conditions can exacerbate the spread of these diseases	Arpitha et al., 2019; Kumar et al., 2021; Altahaan and Dobslaw, 2024; Fakhri and Dobslaw, 2024
	Biological pollution (microbes, viruses)	**Infectious diseases:** Polluted water sources are breeding grounds for pathogens, increasing the incidence of infectious diseases, a significant concern in areas with compromised healthcare systems. War-induced displacement often leads to crowded living conditions, where diseases spread rapidly, especially waterborne illnesses. In war contexts, the lack of reliable information on water quality can lead to the use of contaminated sources, with populations unaware of the associated risks.	Bintsis, 2018; Xiong et al., 2019; Kumar et al., 2021
	Pollution/contamination: aquifers, rivers, sea, groundwater, wetlands, surface water; estuaries	**Diseases and nervous system:** Pollutants like heavy metals, chemicals, and biological agents in water can disrupt the digestive system, leading to gastrointestinal disorders, liver and kidney damage, and in extreme cases, organ failure. Reproductive health can be affected, with exposure to certain pollutants linked to reproductive disorders, developmental issues in fetuses, and reduced fertility. Neurotoxic contaminants in water can affect the nervous system, potentially causing cognitive impairments, neurological disorders, and developmental delays in children. The circulatory system may also be impacted, with some contaminants contributing to cardiovascular diseases. Long-term exposure to certain chemicals and toxins present in contaminated water can increase the risk of cancer. Carcinogens in water can lead to cancers of the bladder, kidney, liver, and other organs. **High death rate:** The combination of polluted water, inadequate nutrition, and weakened healthcare infrastructure in war zones can lead to a higher mortality rate. Vulnerable populations, like children and the elderly, are especially at risk.	Islam and Wong, 2017; Xiong et al., 2019; Kumar et al., 2021; Naidu, 2021; Vandana et al., 2022; Altahaan and Dobslaw, 2024; Fakhri and Dobslaw, 2024
	Acid Rain, pH alteration (river and groundwater)		Altahaan and Dobslaw, 2024; Fakhri and Dobslaw, 2024

This paper also has contributions to practice. The research points to several immediate and long-term interventions necessary to mitigate these environmental and health impacts. In the face of water pollution, there is an urgent need for measures to ensure access to clean water, such as the installation of water filtration systems and the rehabilitation of water supply infrastructure. Soil pollution, which leads to reduced agricultural productivity and heightened health risks, calls for extensive soil remediation efforts and the promotion of sustainable agricultural practices. Air pollution, with its diverse range of health impacts, requires stringent measures to control emissions from military operations and post-conflict reconstruction activities. Lastly, the loss of biodiversity necessitates concerted efforts for habitat restoration and wildlife conservation.

One of the crucial findings of this study is the direct correlation between environmental degradation and increased health risks, particularly in the form of infectious diseases, malnutrition, respiratory problems, and neurological disorders. The deterioration of hygiene conditions, exacerbated by limited access to clean water and the destruction of sanitation facilities, further compounds these health risks. Furthermore, the stress of living in a war environment, coupled with exposure to pollutants and disrupted ecosystems, has profound psychological and physiological effects, elevating the risk of stress-induced mortality and other serious health conditions.

The workshop with Ukrainian experts provided valuable insights, reinforcing the importance of interdisciplinary collaboration in addressing these complex challenges. It highlighted the need for policies and practices that not only focus on immediate conflict resolution but also prioritize environmental restoration and health promotion. This involves not only the cleanup and rehabilitation of contaminated sites but also the implementation of strategies to prevent further environmental damage.

In summary, the environmental impacts of the war in Ukraine have far-reaching and long-lasting implications for human health. Addressing these challenges requires a multifaceted approach, involving environmental restoration, pollution control, healthcare provision, and sustainable development. As the conflict continues to evolve, so too must our strategies for mitigating its environmental and health consequences, ensuring a more resilient and sustainable future for the affected populations and the environment they depend upon.

Finally, it is important to acknowledge a potential limitation regarding the selection of the 15 Ukrainian experts whose perspectives were central to this study. While their expertise in life sciences and deep understanding of the local context are invaluable, relying exclusively on professionals from the conflict zone may introduce a degree of bias in the interpretation of environmental and health impacts. This selection may inherently focus more on localized experiences and potentially overlook broader, perhaps less immediate perspectives that experts from other regions might offer. Such a concentration on a specific group of local experts, although rich in contextual relevance, might limit the generalizability of the findings to other conflict or post-conflict settings. Recognizing this limitation underscores our commitment to a balanced analysis and points to the necessity for further research incorporating a more diverse array of international voices to enrich and verify our conclusions.

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: Conceptualization, Funding acquisition, Supervision, Validation, Writing – original draft, Writing – review & editing. JE: Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. MF: Data curation, Formal analysis, Project administration, Resources, Writing – review & editing, Writing – original draft. TL: Formal analysis, Investigation, Resources, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsrma.2024.1423444/full#supplementary-material

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