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Assessing the impact of the Russian-Ukrainian war on nature: New challenges to sustainable development

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Abstract: One of the global challenges on the path to sustainable management of natural resources is the negative impact of the long-term Russian-Ukrainian war. The purpose of this paper is to highlight the results of the review and ecological and economic assessment of the impact of the Russian-Ukrainian war on natural resources with a special focus special focus on atmospheric air, land, soil and water resources. A theoretical and bibliometric analysis of publications on the impact of the Russian-Ukrainian war on the environment of Ukraine was carried out. The amount of damage caused to the atmospheric air, land and water resources, as well as the natural reserve fund of Ukraine, was summarised. According to preliminary estimates, in the first three years (as of April 2025), the Russian-Ukrainian war caused environmental damage of UAH4.0 tn, which is equivalent to USD99.8 bn or EUR92.2 bn. The largest share in the structure of environmental damage is caused by damage to the nature reserve fund (47.1%) and land resources (30.5%). Water resources accounted for the smallest share (2.9%), while air pollution accounted for 19.5% of total environmental damage. However, this is only a part of the damage documented in accordance with the existing methods in the territories controlled by Ukrainian authorities. Compensation for this damage by reparations should be the basis for the post-war restoration of militarily degraded natural resources. The feasibility of sustainable post-war restoration of agrarian nature use is substantiated, involving the use of sustainable management practices and innovative technologies.

Keywords: air, environmental damage, land, natural resources, pollution, Russian-Ukrainian war, sustainability, water

INTRODUCTION

One of the challenges to sustainable management of agrarian nature use is the ongoing ecocidal Russian-Ukrainian war, which has caused and continues to cause significant damage and losses not only to society and the economy but also to the environment. The issue of assessing the impact of this war on the environment as a whole and its individual components has always been relevant.

A comprehensive analysis of the multifaceted environmental challenges posed by the ongoing Russian-Ukrainian war includes immediate and long-term impacts on air and water quality, soil health, and biodiversity (Yutilova *et al.*, 2025).

Using semi-structured interviews with local residents in three settlements in Kyiv oblast, Elbakidze *et al.* (2025) documented the ecosystem services that people relied on before the war and the changes that have occurred since de-occupation. They documented a significant reduction in access to essential ecosystem services, exacerbated by new negative impacts such as flooding and pollution. The study highlights the vital role of cultural ecosystem services, with many respondents expressing a deep emotional and spiritual connection to their natural environment (Elbakidze *et al.*, 2025).

In assessing the impact of the Russian-Ukrainian war and the destruction of the Kakhovka Dam on biodiversity, Kvach *et al.* (2025) include negative impacts such as toxins and habitat damage from oil spills, shelling, mining, explosions, floods and fires, as well as the neglect of protected areas. At the same time, the positive impacts include a reduction in anthropogenic pressure due to reduced shipping, fishing, recreation, hydraulic engineering, construction, and tourism (Kvach *et al.*, 2025).

The Russian invasion and war have severely impacted Ukraine's forest ecosystems, leading to significant deforestation, habitat degradation and biodiversity loss. As a result, ecosystems have been disrupted, ecological stability altered, and vulnerability to disease and forest fires increased (Velázquez *et al.*, 2025). According to Matsala *et al.* (2025), 18% of protective plantations in the eastern agroforestry region of Ukraine are threatened by the war. Despite this significant damage, the overall loss of the protective function of agricultural land in the study area was relatively small, amounting to 2.7% as of 2023. At the same time, local hotspots showed losses of up to 57%, which correlates with the proximity to the main hostilities that took place in 2022–2023. The majority (81%) of damaged plantations are located on fertile black soil, which facilitates restoration using a variety of native tree species (Matsala *et al.*, 2025).

In analysing land degradation in Ukraine due to hostilities, Novakovska, Belousova and Hunko (2025) focused on soil contamination, infrastructure destruction, and degradation of natural landscapes, including forests and agricultural land. In general, they classified the negative environmental consequences of hostilities as follows: 1) soil and water pollution, 2) changes in the biogeochemical balance of the territory, 3) destruction of water, electricity and gas facilities, 4) destruction of forests and agricultural land, 5) destruction of nature and animals in protected areas, 6) danger to human health (Novakovska, Belousova and Hunko, 2025). Bilyi *et al.* (2025) proposed an algorithm for calculating the degree of soil damage and dust emissions from artillery weapons of various calibres, and estimated the cumulative effect of soil damage and air pollution from explosive products over a day, month, and year. The results of comparing the damage to soil and air emissions from the war are comparable in scale to the work of an average quarry in Ukraine over a year (Bilyi *et al.*, 2025).

A study by Bonchkovskyi *et al.* (2025) showed that craters are sites of secondary geomorphological processes that lead to crater filling and degradation of the surrounding areas. In all analysed craters, an increase in the content of heavy metals, especially cadmium, copper, lead and zinc, was recorded. However, their concentration was mostly only 1.1–1.5 times higher than the background value and almost did not exceed the threshold values in Ukraine. Conversely, the crash sites of a military helicopter and 'fresh' missiles show critical heavy metal contamination. The study also discusses the feasibility of combining data on physical soil disturbance with land use changes to assess the risk of landmines and unexploded ordnance (Bonchkovskyi *et al.*, 2025). Assessing soil contamination in southern Ukraine as a result of military action, Tonkha *et al.* (2025) found high levels of heavy metal contamination, making the use of the study areas unsafe without technical and biological remediation. In many areas, they recommended the removal of topsoil due to its toxicity.

Scientists also emphasise the negative impact of war on organic land use, in particular due to the complication of the process of developing organic production, due to the potential location of organic land in the affected area or directly in the war zone, which is not typical for the organic sector in most countries (Budziak and Budziak, 2025). Given the pollution caused by the war, land can turn from suitable to unsuitable for organic use. In 2022, due to Russia's full-scale military aggression, significant areas of organic land were taken out of circulation, especially in the eastern and southern regions of Ukraine, which resulted in a decrease in the production and sales of organic products to UAH627 mln. However, thanks to the regained territories, the potential of the organic land fund was partially restored in 2023 (Budziak and Budziak, 2025).

Despite considerable attention from scientists and the international community, the problem of a comprehensive assessment of the environmental impact of the Russian-Ukrainian war remains unresolved and requires further research. Therefore, the purpose of this paper is to highlight the results of the review and ecological and economic assessment of the impact of the Russian-Ukrainian war on natural resources with a special focus on atmospheric air, land, soil and water resources.

MATERIALS AND METHODS

At the first stage, a theoretical and bibliometric analysis of publications on the impact of the Russian-Ukrainian war on the environment of Ukraine was conducted. For this purpose, data from the Scopus database for 2014–2024 were used. To form the sample of studies, we implemented the following search strategy: TITLE-ABS-KEY (Ukraine* AND Russia*) AND TITLE-ABS-KEY ("natural resource*" OR "natural environment" OR "atmospheric air" OR land OR soil OR water OR forest OR "natural reserve fund" OR "ecosystem service*" OR "environmental consequence*" OR "environmental damage*") AND TITLE-ABS-KEY ("Russian-Ukrainian war" OR "Russo-Ukrainian war" OR "Russian-Ukrainian conflict" OR "Russo-Ukrainian conflict" OR "Armed conflict" OR war OR conflict OR "military operation*" OR "military action*" OR "armed aggression" OR aggression OR invasion OR "use of force" OR "territorial integrity" OR "military control" OR annexation OR "anti-terrorist operation" OR occupation).

As part of the first stage, scientific mapping of the impact of the Russian-Ukrainian war on individual environmental components was also carried out: atmospheric air, land and soil resources, water resources. For these purposes, the above-mentioned search strategy was alternately changed in terms of the corresponding environmental component: 1) air OR "atmospheric air", 2) land OR soil, 3) water. For theoretical analysis, five documents were selected for each of these three components

according to the following criteria: 1) maximum thematic relevance to the corresponding environmental component, 2) maximum level of citation of the publication.

At the second stage, the amount of damage caused to individual natural components (atmospheric air, land, soil and water resources, as well as the nature reserve fund) and the environment of Ukraine as a whole was summarised. The time range covers the first three years of the full-scale Russian-Ukrainian war (February 2022 – April 2025). The information base is primarily data from the Ministry of environmental protection and natural resources of Ukraine (Ukr.: Ministerstvo zakhystu dovkillia ta pryrodnykh resursiv) and the State environmental inspectorate of Ukraine (DEI – Ukr.: Derzhavna ekolohichna inspektsiia Ukrainy) (Ministry of Environmental Protection and Natural Resources of Ukraine, no date).

RESULTS AND DISCUSSION

ENVIRONMENTAL IMPACTS OF THE RUSSIAN-UKRAINIAN WAR IN UKRAINE: A COMPREHENSIVE BIBLIOMETRIC AND THEORETICAL ASSESSMENT

Bibliometric mapping of the impact of the Russian-Ukrainian war on nature in Ukraine

A combined search of the Scopus database for the above phrases (see methodology section) revealed 676 documents, of which 577 (85.4%) were published in the last three years (2022–2024). The results of the analysis showed that scientists from Ukraine (249 papers or 36.8% of the total), the United States (77 papers or 11.4%), the Russian Federation (51 papers or 7.5%), the United Kingdom (45 papers or 6.7%) and China (43 papers or 6.4%) had the largest number of publications in the studied field. Scientists from the following Ukrainian institutions published the most papers: National Academy of Sciences of Ukraine (Ukr.: Natsionalna akademiia nauk Ukrainy) (44 papers), Taras Shevchenko National University of Kyiv (Ukr.: Kyivskyi natsionalnyi universytet imeni Tarasa Shevchenka) (22 papers), Lviv Polytechnic National University (Ukr.: Natsionalnyi universytet "Lvivska politekhnika") (17 papers).

Analysis of the distribution of documents by research field shows that the main ones include social sciences (25.8% of the total), environmental sciences (15.5%), arts and humanities (12.4%), earth and planetary sciences (7.3%), agricultural and biological sciences (6.4%), economics, econometrics and finance (5.6%), and engineering (5.5%). In general, the conditional share of documents published in economic sciences publications (economics, econometrics and finance; business, management and accounting) was 8.4%.

Analysis of the distribution of documents on the impact of the Russian-Ukrainian war on the environment by type shows that the largest share is made up of articles (451 units or 66.7% of the total number) and conference papers (71 units or 10.5%). Other types of publications include: book chapters (59 units or 8.7%), reviews (38 units or 5.6%), books (17 units or 2.5%), conference reviews (8 units or 1.2%). To construct a bibliometric map, only the indicated types of documents (644 units) were selected. As a result of clustering, the 173 most frequently used terms, used at least five times, were combined into eight clusters, which are marked with different colours. For example, the largest (red) cluster includes 48 keywords, in particular: war, human, remote sensing, agriculture and environment.

The results of chronological clustering indicate the temporal features of the use of key terms during the analysed research period (Fig. 1).

It was found that most terms began to be used intensively during the full-scale invasion of the Russian Federation. For recent years, the most characteristic in terms of intensity was the use of the following keywords:

- 2021: Crimea, political conflict, Belarus, national identify, Black Sea;
- 2022: Russia, conflict, economic development, geopolitics, energy security;
- 2023: Ukraine, Russian Federation, China, human, natural resource, food security;
- 2024: geopolitical risk, ecocide, investment, risk management, environmental management.

The results of the analysis of the 10 most cited articles by Ukrainian authors, according to the Scopus database, showed that they are devoted to the following aspects of the impact of the Russian-Ukrainian war: 1) impact on the environment (Hartmane *et al*., 2024), environmental health (Hryhorczuk *et al*., 2024) and nature in general (Shahini *et al*., 2024), in particular, studies of environmental consequences using remote sensing data (Shevchuk, Vyshnevskyi and Bilous, 2022); 2) impact on water resources and water infrastructure (Shumilova *et al*., 2023), rivers and water systems (Gleick, Vyshnevskyi and Shevchuk, 2023), hydroecosystems (Afanasyev, 2023), water security (Hapich *et al*., 2024a), prospects for alternative water supply for the population of Ukraine (Hapich *et al*., 2024b); 3) impact on soils (Solokha *et al*., 2023).

The results of clustering by country indicate the features of cooperation between countries in conducting research and publishing their results during 2014–2024 (Fig. 2). Based on the clustering of 32 countries that had at least five publications each, six clusters were identified, which are marked with different colours.

First cluster (red) includes seven countries: Australia, Brazil, Lithuania, Norway, Portugal, Slovakia, and Spain. The second cluster (green) included six countries: Australia, the Czech Republic, Hungary, Iran, Poland, and South Africa. The third cluster (blue) was formed by six countries: China, France, India, Pakistan, Saudi Arabia, and Turkey. The fourth cluster (yellow) includes five countries: Belgium, Canada, Kazakhstan, Latvia, and Sweden. The fifth cluster (purple) includes five countries: Germany, Italy, Romania, Ukraine, and the United States. The sixth cluster (light blue) includes three countries: the Netherlands, Switzerland, and the United Kingdom.

Intensive international cooperation in studying the impact of the Russian-Ukrainian war, firstly, confirms the significant scientific interest in this issue from different countries and its global scale; secondly, it is an additional argument in the context of documenting the environmental crimes of the Russian Federation. Intensification of Ukraine's cooperation with other countries of the world is among the priority areas for the development of research in this area in terms of forming an evidence base for holding the Russian Federation accountable and compensating for the damage caused.

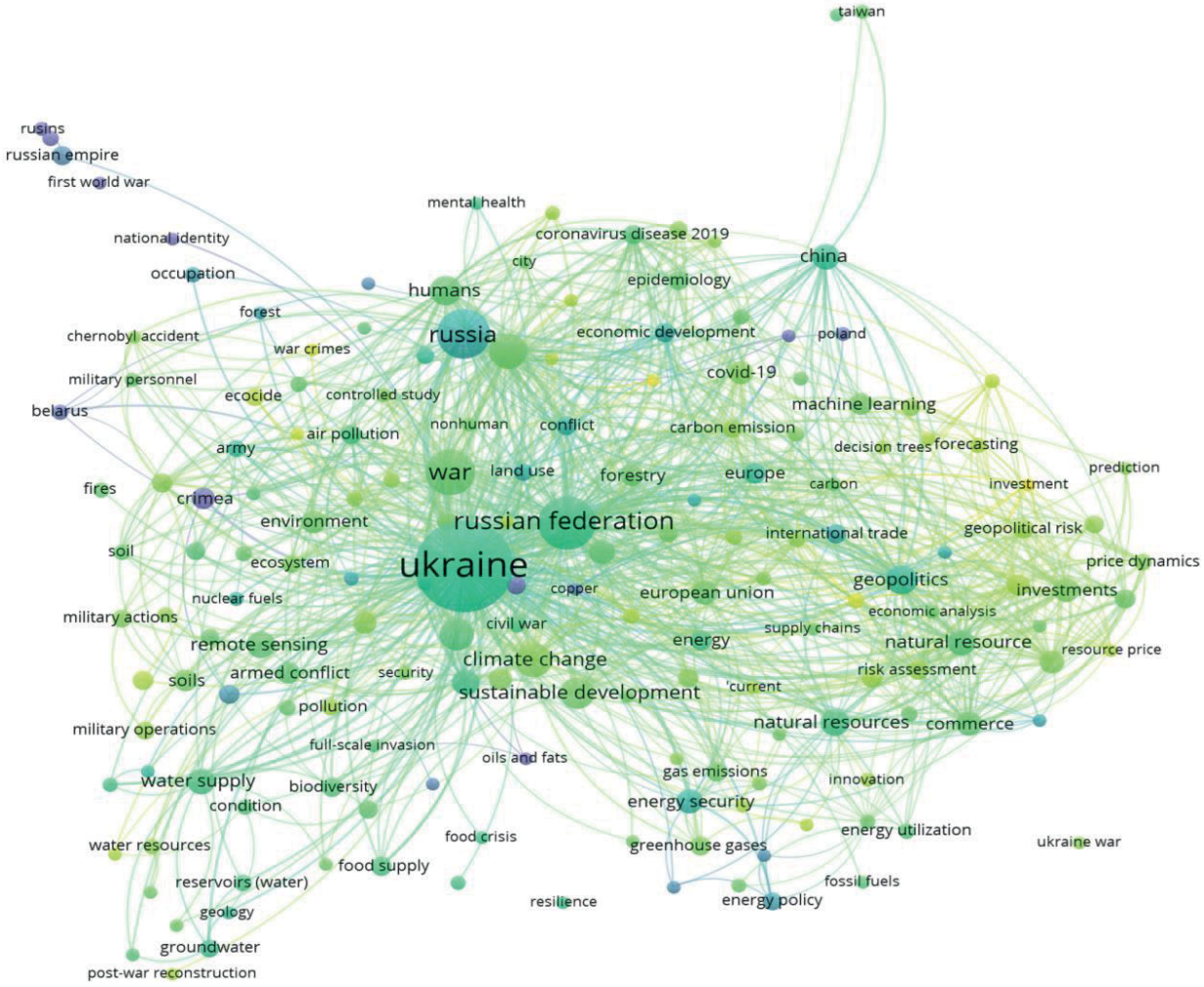

Fig. 1. Bibliometric map of the chronology of the use of the most frequently used terms in publications on the impact of the Russian-Ukrainian war on the environment, 2014–2024; source: own elaboration based on Scopus data using VOSviewer

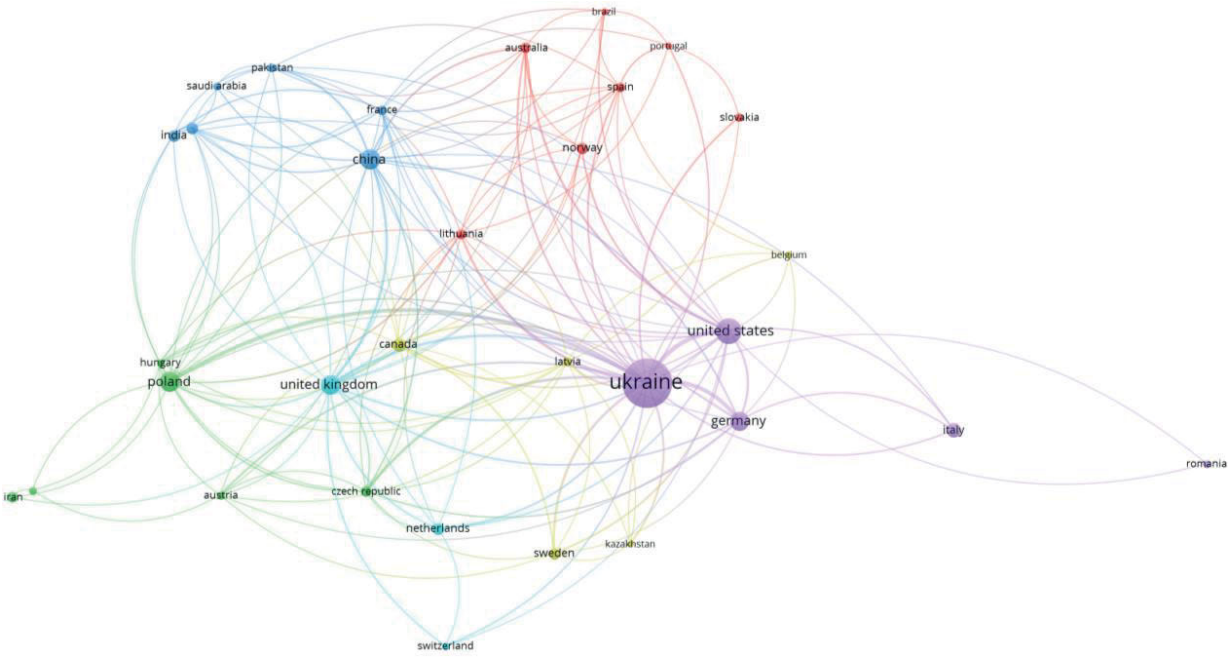

Fig. 2. Bibliometric map of the chronology of the use of the most frequently used terms in publications on the impact of the Russian-Ukrainian war on the environment, 2014–2024; source: own elaboration based on Scopus data using VOSviewer

The impact of the Russian-Ukrainian war on atmospheric air

As a result of a combined search in the Scopus database, 64 documents containing keywords about the impact of the Russian-Ukrainian war on atmospheric air were identified. Bibliometric analysis of the metadata of these documents revealed four clusters that combined 22 keywords that were used at least three times (Fig. 3):

- the first cluster (red) includes nine words, among which the most frequently occurring: ecocide, Russian Federation, air pollution;
- the second cluster (green) includes seven words, among which the most frequently occurring: air transportation, air traffic control, air traffic;
- the third cluster (blue) includes four words, among which the most frequently occurring: war, food security, soils;
- the fourth cluster (yellow) includes two words: Ukraine and energy security.

The analysis of spatial and temporal changes in air quality shows both direct and indirect impacts of the Russian-Ukrainian war, and these impacts extend far beyond the borders of certain countries. Russia's full-scale war against Ukraine has caused significant air pollution and accelerated global warming, in particular due to numerous missile strikes on industrial facilities, forest fires, especially near the front line, burning oil and ammunition depots, destruction of urban and industrial areas, the use of military equipment and other accidents, as well as various processes resulting from the war (Savenets *et al*., 2023; Kabylda *et al*., 2024).

Based on the open remote sensing data from the Sentinel-5P satellite over Ukraine in 2022, a significant increase in the air quality index (AQI) was recorded, indicating the presence of smoke and dust in the air. At the same time, based on the assessment and analysis of NO_2, SO_2, CO and HCHO densities, as well as O_3 density and the absorbing aerosol index (AAI), a decrease in emissions of primary air pollutants and a high level of atmospheric recovery compared to 2021 (the year before the war) were found (Davybida, 2023). An assessment of changes in air pollution after the first year of full-scale war based on NO_2 and CO levels from the troposphere monitoring instrument (TROPOMI) showed different intensities of this impact depending on a number of factors. The most important changes were observed during the first months of the war, showing a decrease in NO_2 levels in large cities, an increase in NO_2 near the borders, including eastern and north-eastern Ukraine, and elevated CO levels during forest fires near the frontline. The impacts of the war on cities varied according to their distance from the frontline, critical infrastructure, and occupied-unoccupied status (Savenets *et al*., 2023).

Russia's military invasion of Ukraine has led to the closure of Ukrainian airspace to civil aviation and restricted the use of Belarusian and Russian airspace due to military activities and war-related sanctions (Ostroumov, Ivashchuk and Kuzmenko, 2022; Ivannikova, Sokolova and Cherednichenko, 2024). The airspace closures have forced airlines to make detours and look for alternative routes; this leads to a significant increase in flight times on routes connecting Europe and Asia, North America and Asia, and North America and the Middle East (Ivannikova, Sokolova and Cherednichenko, 2024). All closed airspaces together form a barrier along the eastern border of the European Union, with a significant impact on north-south polar flights (Ostroumov, Ivashchuk and Kuzmenko, 2022). Significant fuel overruns on the re-routed route lead to higher ticket prices and increased carbon dioxide emissions (Ostroumov, Ivashchuk and Kuzmenko, 2022). The analysis (based on the example of three European airlines: Finnair, LOT Polish and Lufthansa Airlines) shows an increase in airline operating costs and CO_2 emissions from 18% to 40% on certain routes after airspace closures (Ivannikova, Sokolova and Cherednichenko, 2024).

Given the scarcity and difficulty of obtaining information on air quality, scientists consider the possibility of implementing an effective monitoring system and the need to improve the methodology for assessing environmental losses and damage, as well as procedures for bringing perpetrators to justice (Kabylda *et al*., 2024), substantiate the important role of remote sensing for detecting and assessing short- and long-term air pollutant emissions (Savenets *et al*., 2023), develop a forecast of global CO_2 emissions from aviation for the next five years under two different scenarios. To stabilise the environmental situation, it is proposed to combine management, regulatory and practical measures, with priority given to preventive measures (Kabylda *et al*., 2024).

The impact of the Russian-Ukrainian war on land and soil resources

A combined search of the Scopus database revealed 139 documents containing keywords about the impact of the Russian-Ukrainian war on land and soil resources. A bibliometric analysis of the metadata of these documents revealed six clusters that unite 24 keywords that were used at least five times (Fig. 4):

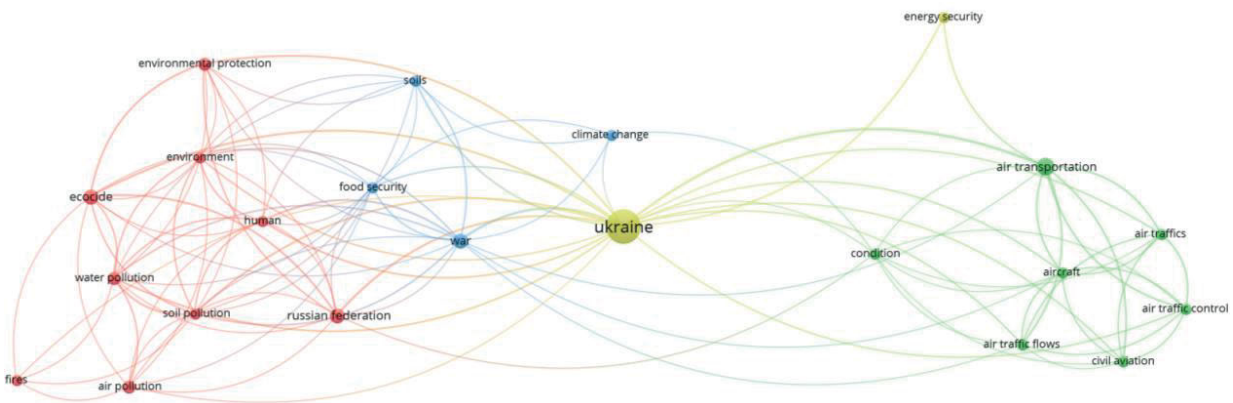

Fig. 3. Bibliometric map of the most frequently used terms in publications on the impact of the Russian-Ukrainian war on atmospheric air, 2014–2024; source: own elaboration based on Scopus data using VOSviewer

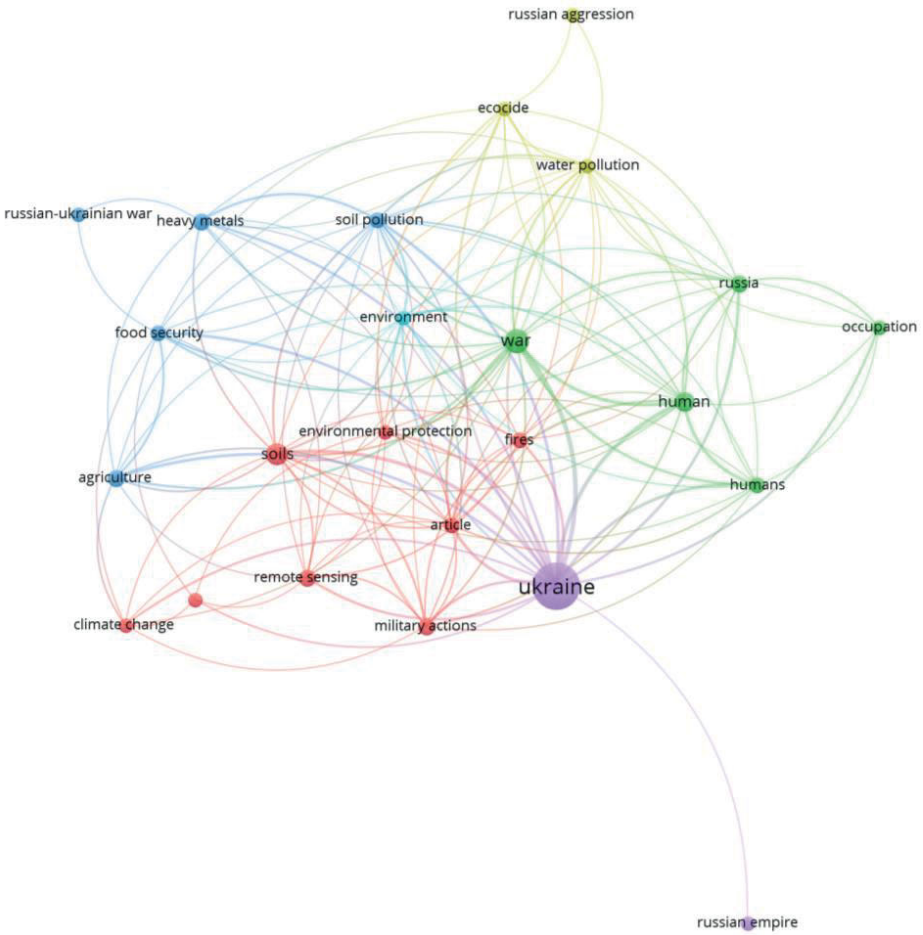

Fig. 4. Bibliometric map of the most frequently used terms in publications on the impact of the Russian-Ukrainian war on land and soil resources, 2014–2024: source: own elaboration based on Scopus data using VOSviewer

- the first cluster (red) includes eight words, among which the most frequently occurring: soils, environmental protection, military actions;
- the second cluster (green) includes six words, among which the most frequently occurring: war, Russian Federation, human;
- the third cluster (blue) includes four words, among which the most frequently occurring: soil pollution, food security, heavy metals;
- the fourth cluster (yellow) includes three words: ecocide, Russian Federation, water pollution;
- the fifth cluster (purple) includes two words: Ukraine, Russian Empire;
- the sixth cluster (light blue) includes one word: environment.

War has an unprecedented impact on land and soil resources, as they are the battlefields. The literature covers the issue of assessing the impact of the armed aggression of the Russian Federation on the soil resources of Ukraine in more detail, while land resources and land use were less frequently studied. To assess the impact of hostilities on soils, scientists more often used remote methods, while field research methods were less often used.

In particular, Ukrainian scientists have introduced a new type of soil degradation: degradation caused by armed aggression (military type), which includes the following subtypes: 1) mechanical, 2) physical, 3) chemical, 4) physical-and-chemical, 5) biological, and 6) other areas of impact on soils and land plots. Maps of the impact of military actions on the soil cover at different levels of government (Ukraine, oblast, rayon, territorial community) have been developed. The areas of each type of soil affected by the hostilities and requiring further research, monitoring and control have been identified. As of March 2023, the largest area affected by hostilities is characteristic of chernozem soils: ordinary chernozem (5.0 mln ha), southern chernozem (2.1 mln ha), typical and podzolic (1.9 mln ha), meadow soils and meadow-chernozem (0.2 mln ha). According to the area criterion, chernozems suffered the most; in some areas, soils were destroyed (Baliuk *et al*., 2024). Scientific publications most often document cases of chemical soil degradation, including soil contamination, in different regions with different intensities of hostilities.

The article by Solokha *et al*. (2023) is one of the first papers to publish field research data during this full-scale Russian-Ukrainian war. The results showed that the amount of fine sediments increased in the shelled areas compared to the non-shelled areas. There was also an increase in the content of heavy metals (e.g., manganese, iron, cobalt, copper, cadmium, chromium, lead and nickel) in the soils in the shelled areas compared to the non-shelled areas. The analysis of remote sensing data showed that on a large scale (eastern and south-eastern Ukraine), green vegetation decreased in 2022 compared to 2021 in areas where the fighting was more intense (Luhansk and Donetsk). On a small scale (in the Kharkiv region), vegetation greenness was

affected by bombardment. Shelling increases soil contamination and contributes to a decrease in green vegetation where hostilities are intense (Solokha *et al*., 2023).

The debris of destroyed military equipment, ammunition and fuel residues leads to multifactorial damage to the soil system, causing local and global pollution and loss of soil resources. In all the studied cases of the Kharkiv region, mechanical, chemical and physical degradation of soils was recorded. This was manifested in changes in particle size distribution in explosion sites, burning zones and areas of heavy metal contamination. The equipment incineration resulted in a 1.2–1.8-fold increase in the sand fraction and a 1.1–1.2-fold decrease in the clay fraction. The level of soil contamination with heavy metals significantly exceeded sanitary standards; the highest levels of contamination were recorded for Pb, Zn and Cd. In all affected areas, there were changes in the structure of the microbiome (20.5-fold increase in the proportion of mycelial organisms), inhibition of microbiological processes (1.2-fold decrease), reduction of microbial biomass (2.1-fold decrease), and high soil toxicity (99.8%). The results indicate that explosions and pyrolysis of armoured vehicles have a significant impact on soil mesobiota and plants (Solokha *et al*., 2024).

The analysis of soil pollution in Kharkiv, Kherson and Zaporizhzhia regions shows that the intensity of pollution depends on the location, industrial development and the course of hostilities. Illegal dumping of chemical waste and active hostilities have caused significant soil contamination with heavy metals and oil products: in the Kharkiv region, there was a 200% increase in Cd pollution; in the Kherson and Zaporizhzhia regions, there was a 139% and 156% increase in oil spills. All these cases had serious consequences for public health and the environment (Shebanina *et al*., 2024). In contrast to the above results, Petrushka, Petrushka and Yukhman (2023) assessed the impact of military actions on urban soils in a region with relatively lower intensity of hostilities (using the city of Lviv as an example). It was found that the values of the environmental risk index of each element based on the Nemerov index show a very high level of pollution (Ps = 48.64), which exceeds the permissible value by 15 times. The highest environmental risk factor (Er) is generated by Cd. The studied elements in terms of the environmental risk factor are arranged in the following sequence: Cd > Cu > Pb > Ni > Zn > Cr > Ti. All the elements studied, except for titanium and chromium, have a significant and very high environmental risk potential (Petrushka, Petrushka and Yukhman, 2023).

The impact of the Russian-Ukrainian war on water resources

A combined search in the Scopus database revealed 88 documents containing keywords on the impact of the Russian-Ukrainian war on water resources. As a result of the bibliometric analysis of the metadata of these documents, three clusters were formed, uniting 23 keywords that were used at least five times (Fig. 5):

- the first cluster (red) includes nine words, among which the most frequently occurring: water resources, reservoirs (water), ground water;
- the second cluster (green) includes eight words, among which the most frequently occurring: Ukraine, Russian Federation, war;
- the third cluster (blue) includes six words: military operations, water supply, sustainable development.

The Russian Federation is using water supply as a weapon in its war against Ukraine. Rivers have long played the role of physical barriers during military conflicts, but in the Russian-Ukrainian war, water and built water systems have also been targeted and used as both offensive and defensive weapons (Gleick, Vyshnevskyi and Shevchuk, 2023). Based on an analysis

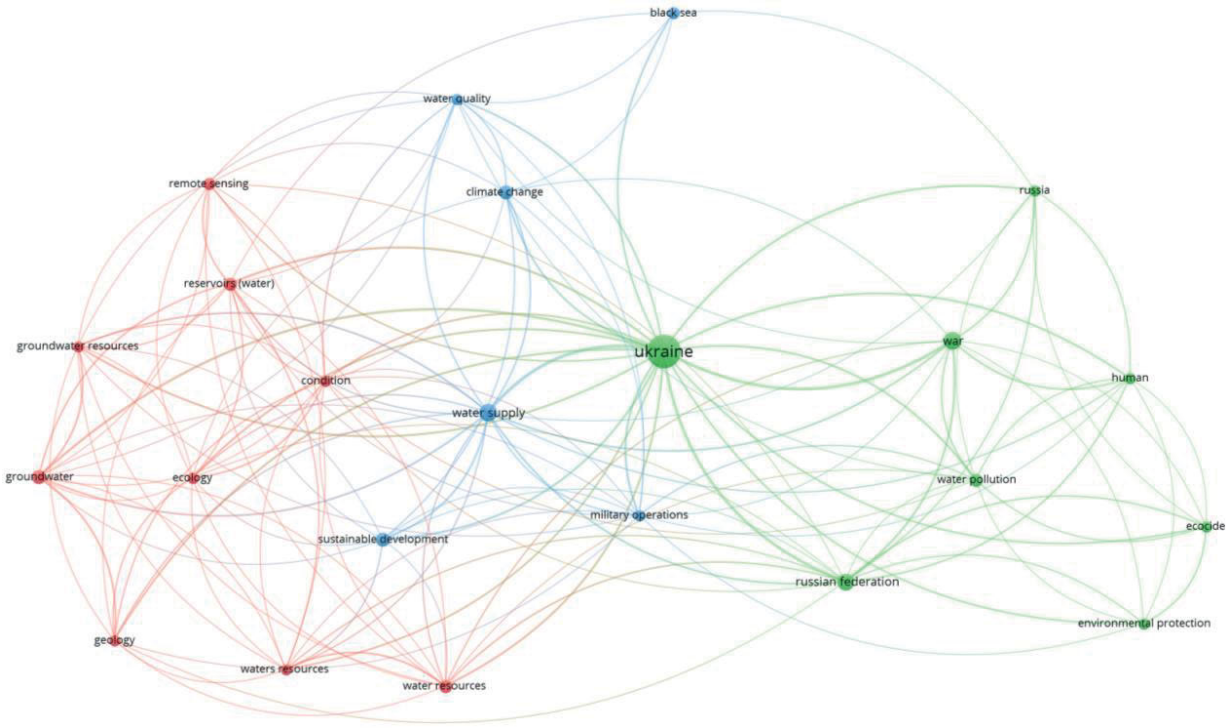

Fig. 5. Bibliometric map of the most frequently used terms in publications on the impact of the Russian-Ukrainian war on water resources, 2014–2024; source: own elaboration based on Scopus data using VOSviewer

of the multifaceted impacts of hostilities on Ukraine's freshwater resources and water infrastructure during the first three months of full-scale war, researchers identified the nature of the impacts, the types of pressure exerted on the water sector, and the negative consequences for the availability and quality of freshwater for civilians. The results showed that many water infrastructures, such as dams on reservoirs, water supply and treatment systems, and underground mines, have been damaged or threatened by the hostilities (Shumilova *et al*., 2023).

Russia is systematically destroying Ukraine's water infrastructure. Russian troops destroyed one-third of Ukraine's freshwater reserves between February 2022 and 2024 (approximately 19 km^3), worth more than USD18 bn; damage to canals, pipelines, pumping stations and water supply systems has left more than 5 mln people without drinking water. The loss of hydrostatic pressure in the Kakhovka reservoir is altering storage and flow in aquifers and surface waters, as well as water intake facilities (Hapich *et al*., 2024b). Scientists have also highlighted the damage to commercial and recreational fisheries, including the loss of coastal areas and spawning grounds (Hapich *et al*., 2024a). As of June 2023, more than 500 water infrastructure facilities were destroyed, and more than 16,000 km^2 of rivers were contaminated with mines and explosives (Stelmakh *et al*., 2023).

The war not only destroys the water supply infrastructure but also contaminates natural waters with sewage and ammunition. As a result, the hydroecological status of Ukraine's natural watercourses and reservoirs is deteriorating. The key consequences of military actions on water bodies include the destruction of water infrastructure and hydraulic structures, contamination with explosives and destroyed military equipment, flooding with mine water and leaks from tailing ponds, and deterioration in water quality (Stelmakh *et al*., 2023). Scientists have identified the negative geophysical, hydrological and environmental impacts of the Russian-Ukrainian war on major rivers and water infrastructure in Ukraine, focusing on the dams and reservoirs of the Dnipro River and major tributaries, as well as the destruction of the Kakhovka Dam in June 2023 (Gleick, Vyshnevskyi and Shevchuk, 2023).

The scale and severity of the current negative impacts on water resources and water security are unprecedented, raising important questions of international law and how the international legal and scientific communities should respond (Gleick, Vyshnevskyi and Shevchuk, 2023). This is all the more important as the ongoing Russian-Ukrainian war continues to have numerous negative impacts on sustainable development not only in Ukraine but also globally, impeding the achievement of clean water and sanitation, the conservation and sustainable use of water resources, and energy and food security (Shumilova *et al.* 2023).

Based on the analysis of the main elements of the structure of water supply, water distribution and wastewater discharge in the river basins of Ukraine, the researchers substantiate the prospects and technological solutions for alternative water supply for the war-affected regions through the construction of groundwater extraction wells (Hapich *et al*., 2024b), discuss different approaches to ecosystem management and options for the future reconstruction of the Kakhovka reservoir, and propose strategic options for the development of the water sector to ensure water security in the post-war period. The priority ways of post-war water resources recovery include: restoring critical water sector infrastructure, systematic biochemical analysis of water, clearing military debris with the help of volunteers, and involving reparations in the water sector, attracting investors (Stelmakh *et al*., 2023).

ECOLOGICAL AND ECONOMIC ASSESSMENT OF THE IMPACT OF THE RUSSIAN-UKRAINIAN WAR ON ENVIRONMENTAL COMPONENTS IN UKRAINE

At the second stage, the amount of damage caused to atmospheric air, land, soil and water resources, as well as the nature reserve fund of Ukraine, was summarised.

The total amount of damage due to air pollution in Ukraine as a result of the Russian-Ukrainian war is about UAH779.0 bn, which is equivalent to USD19.4 bn or EUR17.9 bn (Tab. 1). The total amount of emissions (nitrogen oxides, ammonia,

Table 1. Approximate ecological and economic assessment of damage to atmospheric air due to the Russian-Ukrainian war (as of 30.04.2025)

Indicator	Documented extent of damage and losses caused by Russian armed aggression	Discharge into atmospheric air (thous. Mg)	Estimated damage calculated based on the DEI in accordance with approved methods			
			bn UAH	bn USD[1)]	bn EUR[1)]	%
Forest fires (area of burned forests and other plantations; ha)	85,913	62,146.8	633.24	15.77	14.57	81.3
Oil product fires (amount of burned oil, petroleum products and gas; Mg)	3,100	10,863.6	139.70	3.48	3.22	17.9
Burning of other objects (area of other burned objects; m^2)	2,559	247.6	6.05	0.15	0.14	0.8
Emissions of poisonous substances into the air	–	0.181	0.0072	0.0002	0.0002	0.0
Consequences of military actions on the atmospheric air (total)	–	73,238.2	779.00	19.40	17.93	100.0

[1)] Calculations made by the authors are based on the average annual (2024) official exchange rate of the hryvnia (UAH) against foreign currencies: UAH40.15 = USD1; UAH43.45 = EUR1.
Explanation: DEI = State environmental inspectorate of Ukraine (Ukr.: Derzhavna ekolohichna inspektsiia Ukrainy).
Source: own study based on data of Ministry of Environmental Protection and Natural Resources of Ukraine (no date) acquired in 2025.

sulphur dioxide, benzo(a)pyrene, non-methane volatile organic compounds, carbon monoxide, carbon dioxide, particulate matter, metals and their compounds) due to military actions into the atmosphere is about 73.2 mln Mg, with about 80% of these emissions caused by forest fires. Forest fires on an area of 85.9 thous. ha caused damage in the amount of UAH633.2 bln, which is 81.3% of the total damage to the atmospheric air. The smallest share in the structure of emissions into the atmosphere is occupied by the mass of unorganised emissions of other pollutants or mixtures of such substances, which is 181 Mg.

The total amount of damage due to land clogging and soil pollution in Ukraine as a result of the Russian-Ukrainian war is about UAH1220.7 bn, which is equivalent to USD30.4 bn or EUR28.1 bn (Tab. 2).

Land clogging on an estimated area of 23,116 thous. m^2 caused damage in the amount of UAH1,200 bn (on average UAH51.912 thous. per m^2), which is about 98.3% of the damage caused to Ukraine's land resources under the two analysed damage items. At the same time, it should be noted that the damage to land and soil resources caused by the war is not limited to these two items, including a much wider range of aspects of military land degradation, as discussed in our publications (Baliuk *et al*., 2024; Kucher and Kucher, 2024).

The total amount of damage due to land clogging and soil pollution in Ukraine as a result of the Russian-Ukrainian war is about UAH116.9 bn, which is equivalent to USD2.9 bn or EUR2.7 bn (Tab. 3).

Pollution of water bodies (sea and non-sea water) caused more than half (62.6% or UAH73.15 bn) of the total damage to water resources of Ukraine. The total mass of pollutants released into the water is 48,007 Mg, including: non-sea waters – 47,940 Mg, sea waters – 67 Mg. The Russian Federation has arbitrarily (illegally) withdrawn and/or used more than 21 bn m^3 of water, which caused damage in the amount of about UAH34.0 bn (29.1% of the total amount of damage to water resources).

The main environmental and economic consequences of the Russian Federation's blowing up (destruction) of the dam of Kakhovka Hydroelectric Power Plant (HPP) should be noted separately: the estimated amount of environmental damage caused by this disaster is UAH146.4 bn, which is equivalent to USD3.64 bn or EUR3.37 bn. The volume of water decreased by 14.395 km^3 (i.e., more than 72% of the water from the Kakhovka reservoir was lost); the area of flooded forests is 63,447 ha; 1144 households were affected.

According to the State environmental inspectorate of Ukraine (DEI – Ukr.: Derzhavna ekolohichna inspektsiia Ukrainy), the

Table 2. Approximate ecological and economic assessment of damage to land resources due to the Russian-Ukrainian war (as of 30.04.2025)

Indicator	The area of clogged/littered and contaminated soils caused by Russian armed aggression (thous. m^2)	Estimated damage calculated based on the DEI in accordance with approved methods			
		bn UAH	bn USD[1)]	bn EUR[1)]	%
Clogging/littering of lands	23,116.0	1,200.00	29.89	27.62	98.3
Soil pollution/contamination	1,178.3	20.69	0.52	0.48	1.7
Consequences of military actions on the land resources (total)	24,294.3[2)]	1,220.69	30.41	28.10	100.0

[1)] As in Tab. 1. [2)] The total area is conditional, since the same land plot can be simultaneously clogged and contaminated.
Explanation: DEI as in Tab. 1.
Source: own study based on data of Ministry of Environmental Protection and Natural Resources of Ukraine (no date) acquired in 2025.

Table 3. Approximate ecological and economic assessment of damage to water (aquatic) resources due to the Russian-Ukrainian war (as of 30.04.2025)

Indicator	Documented extent of damage and losses caused by Russian armed aggression	Estimated damage calculated based on the DEI in accordance with approved methods			
		bn UAH	bn USD[1)]	bn EUR[1)]	%
Water pollution (water bodies; Mg)	47,940	65.12	1.62	1.50	55.7
Clogging of water bodies (mass of foreign objects, materials, waste and/or other substances in water bodies; Mg)	42,364	9.76	0.24	0.22	8.3
Arbitrary use of water (volume of water collected/used is arbitrary; mln m^3)	21,049	34.03	0.85	0.78	29.1
Pollution of sea waters (mass of pollutants that have entered seawater; Mg)	67	8.03	0.20	0.18	6.9
Consequences of military actions on the water resources (total)	–	116.94	2.91	2.68	100.0

[1)] As in Tab. 1.
Explanation: DEI as in Tab. 1.
Source: own study based on data of Ministry of Environmental Protection and Natural Resources of Ukraine (no date) acquired in 2025.

following damages were caused by the undermining of the Kakhovka HPP by the armed forces of the Russian Federation on 06.06.2023: UAH46.55 bn – to the National Nature Park (NPP – Ukr.: Natsionalnyi pryrodnyi park) "Nyzhnodniprovskyi"; UAH15.3 bn – to the NPP "Velykyi Luh"; UAH73.27 bn – to the NPP "Kamianska Sich" (Ministerstvo zakhystu dovkillia ta pryrodnykh resursiv Ukrainy, 2023). The total amount of damage due to natural reserve fund in Ukraine as a result of the Russian-Ukrainian war is about UAH1888.4 bn, which is equivalent to USD47.0 bn or EUR43.5 bn (Tab. 4). It should be noted that this component of damage is complex, as it integrates damage caused to various resources in protected areas.

The largest amount and, accordingly, the share in the structure of damage caused to the Ukrainian nature reserve fund is attributed to the following types of losses: 1) burned forests and other plantations, 2) destroyed and damaged trees and plants, 3) damaged vegetation / plant world, 4) destroyed objects of the animal world. Analysing the damage to the nature reserve fund in terms of natural resources, it should be noted that the damage caused by land clogging (3,116 m^2) and soil contamination (10,600 m^2) amounted to UAH1.211 bn. As a result of the destruction and damage of trees and plants (69,192 thous. pcs.), as well as damage to the plant world (21,932 ha), damage was caused in the amount of UAH894.22 bn. As a result of hostilities, 75,110 objects of the animal world were destroyed, which caused damage in the amount of UAH162.92 bn.

Thus, according to preliminary estimates, as of April 2025, the Russian-Ukrainian war caused environmental damage of UAH4,005.1 bn, which is equivalent to USD99.8 bn or EUR92.2 bn (Tab. 5).

Table 4. Approximate ecological and economic assessment of damage to natural reserve fund due to the Russian-Ukrainian war (as of 30.04.2025)

Indicator	Documented extent of damage and losses caused by Russian armed aggression	Estimated damage calculated based on the DEI in accordance with approved methods			
		bn UAH	bn USD[1)]	bn EUR[1)]	%
Clogging/littering of lands (the land is littered; m^2)	3,116	0.702	0.02	0.02	0.0
Soil pollution/contamination (contaminated soil; m^2)	10,600	0.509	0.01	0.01	0.0
Forest fires (area of burned forests and other plantations; ha)	16,428	830.09	20.67	19.10	44.0
Burning of other objects (area of other burned objects; m^2)	203	0.00004	0.00	0.00	0.0
Destruction and damage to trees and plants (number of destroyed and damaged trees and plants; thous. pcs.)	69,192	723.24	18.01	16.65	38.3
Damage to vegetation/plant world (area of damaged vegetation; ha)	21,932	170.98	4.26	3.94	9.1
Destruction of objects of the animal world (number of destroyed objects; pcs.)	75,110	162.92	4.06	3.75	8.6
Domestic littering of territories	–	0.00004	0.00	0.00	0.0
Consequences of military actions on the natural reserve fund (total)	–	1,888.44	47.03	43.47	100.0

[1)] As in Tab. 1.
Explanation: DEI as in Tab. 1.
Source: own study based on data of Ministry of Environmental Protection and Natural Resources of Ukraine (no date) acquired in 2025.

Table 5. Approximate ecological and economic assessment of the impact of the Russian-Ukrainian war on environmental components in Ukraine (as of 30.04.2025)

Indicator	Documented facts of causing damage and losses as a result of Russian armed aggression	Estimated damage calculated based on the DEI in accordance with approved methods			
		bn UAH	bn USD[1)]	bn EUR[1)]	%
Damages caused to atmospheric air	1,622	779.00	19.40	17.93	19.5
Damages caused to land resources	2,912	1,220.69	30.41	28.10	30.5
Damages caused to water resources	216	116.94	2.91	2.68	2.9
Damages caused to natural reserve fund	11	1,888.44	47.03	43.47	47.1
Consequences of military actions and impact on the environment (total)	8379	4,005.07	99.75	92.18	100.0

[1)] As in Tab. 1.
Explanation: DEI as in Tab. 1.
Source: own study based on data of Ministry of Environmental Protection and Natural Resources of Ukraine (no date) acquired in 2025.

According to calculations, as of April 2025, the largest share in the structure of environmental damage was damage to the nature reserve fund (47.1%) and land resources (30.5%). Damage to water resources accounted for the smallest share (2.9%), while damage to atmospheric air accounted for 19.5% of total environmental damage. It should be noted that all the amounts of damage presented in this paper are preliminary, and their final value will be determined after the end of the war.

CONCLUSIONS

This paper highlights the results of the review and ecological and economic assessment of the impact of the Russian-Ukrainian war on natural resources, with a particular emphasis on atmospheric air, land, soil and water resources. The theoretical and bibliometric analysis of publications on the impact of the Russian-Ukrainian war on nature in general and individual components of Ukraine's environment (atmospheric air, land and soil resources, water resources) allowed us to identify the main clusters and areas of research and the most topical issues. Scientific documentation and mapping of research is an additional source and evidence base for bringing the Russian Federation to justice and compensation for damages.

According to preliminary estimates, as of April 2025, the Russian-Ukrainian war caused environmental damage of UAH4.0 tn, which is equivalent to USD99.8 bn or EUR92.2 bn. The largest share in the structure of environmental damage was damage to the nature reserve fund (47.1%) and land resources (30.5%). Damage to water resources accounted for the smallest share (2.9%), while damage to atmospheric air accounted for 19.5% of total environmental damage. The compensation to Ukraine for the losses caused by the armed aggression of the Russian Federation in the form of reparations should become the basis for the post-war restoration of militarily degraded natural resources. The post-war restoration of agrarian nature use should be based on the principles of sustainability and innovation, which involve the use of sustainable management practices and innovative technologies. Ensuring the sustainable post-war restoration of agrarian nature use is appropriate and critically important for several reasons, including: the need to adapt to climate change, ensuring food and environmental security, preserving and developing rural areas, obtaining international support and attracting investment, environmental responsibility and fulfilling international obligations. Implementation of sustainable agricultural practices during post-war reconstruction will open up greater opportunities for access to funding from the European Union, the United Nations, the World Bank and other donors, and will also help Ukraine to fulfil international environmental agreements, including commitments to reduce emissions and protect biodiversity.

The priority practices for sustainable post-war restoration of agrarian nature use include the following groups: 1) sustainable soil management practices, 2) sustainable water management practices, 3) integrated sustainable soil and water management practices. Specific sustainable practices and technologies that deserve to be implemented include the following: organic farming; conservation farming; low-carbon farming; minimal and/or no-till farming, mulching; crop rotation and diversification; cover crops and green manure; agroforestry and agroforestry reclamation; use of natural fertilisers, biological plant protection products and microbiological preparations; integrated nutrient management (combination of organic and inorganic fertilisers); recycling of agricultural waste and use of organic residues (composts, vermicompost, etc.); phytoremediation; precision fertiliser and water application; drip irrigation; automated and smart irrigation; use of drought-resistant plant varieties; recycling and reuse of water (irrigation or waste water); integrated soil and sediment management. The issue of sustainable post-war restoration of natural resources requires additional research in the future.

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CONFLICT OF INFERESTS

All authors declare that they have no conflict of interests.

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