

RETURN: Restoring Environments in Ukraine

The impact of military actions on the natural
environment in Ukraine

Review of the results of scientific research, analytical assessments,
and reports based on materials published in open access

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Kyiv – Uppsala – 2025

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DESTROYED
KRYACHKY OIL
DEPOT. KYIV REGION,
20 OCTOBER 2022.

Introduction

The military aggression of the Russian Federation (RF) against Ukraine began in 2014 when regular military units, using conventional weaponry, occupied parts of Ukraine's Donetsk and Luhansk regions. After intense battles, the Ukrainian Armed Forces managed to halt the enemy, though territories in Donetsk and Luhansk oblast were under occupation, and there remained a frontline in these regions. At this time, Ukraine's Crimean Autonomous Republic had fallen under Russian control, having been seized by force but without direct military clashes. Still, heavy combat engagements ceased until February 24, 2022.

On February 24, 2022, Russia launched a full-scale invasion of Ukraine, swiftly occupying one-third of the country's territory. However, the rapid advance of Russian forces was eventually halted, and by November 2022, after fierce battles, the Armed Forces of Ukraine managed to liberate parts of the occupied territories in Kyiv, Chernihiv, Sumy, Kharkiv, Zaporizhzhia, and Kherson regions. As of late January 2025, intense fighting continues along the frontline stretching through Kherson, Zaporizhzhia, Donetsk, and Luhansk regions. The enemy is slowly advancing northward, suffering heavy losses but still seizing new Ukrainian territories.

At the same time, almost the entire territory of Ukraine has become a target for artillery shelling, missile strikes, and drone attacks. The actions of Russian ground forces and aviation, along with missile and drone strikes, have caused massive destruction to residential infrastructure, industrial facilities, and the agricultural sector. The war has resulted in the deaths of hundreds of thousands of military personnel and civilians, the

migration of millions abroad, and the displacement of millions more from combat zones to remote regions of Ukraine. Russian military aggression has also inflicted immense environmental destruction. Vast areas of natural and protected territories have been devastated or affected by fires caused by military activity. Large regions remain mined and contaminated with unexploded ordnance. Moreover, many areas are polluted with hazardous chemical residues from used munitions and destroyed industrial facilities. Water bodies in combat zones or those hit by missiles and drones have suffered similar damage. Military actions have undeniably had a devastating impact on Ukraine's natural ecosystems and rich biodiversity.

Unfortunately, Russia's aggression continues, and the destruction of both the natural and human-made environment persists. However, from the very beginning of the full-scale war, relevant state authorities have been documenting environmental violations and assessing ecological damages. Representatives of the academic sector, with support from international partners, have focused their research efforts on evaluating environmental damage, monitoring the military impact, studying recovery processes, and identifying threats to natural systems and human well-being. These assessments and research findings have been published in numerous scientific, popular science, and analytical publications, which require further summarization and serious analysis.

The goal of this study is to review publicly available sources and identify the main directions and trends in analytical, investigative, monitoring, scientific, and other research conducted in Ukraine and abroad on the military impact on the environment. It also aims to highlight possible gaps that require further attention from researchers and policymakers. We have attempted to gather and analyse, or at least review, as many accessible publications as possible, but we acknowledge that not all relevant sources may have come to our attention.

Key Terminology and Concepts

In the context of this study, we use the following terms and concepts:

Military activity includes combat operations and their logistical support. Key forms of combat operations include:

- Direct offensive and/or defensive military engagements
- Artillery, mortar, and missile strikes, air raids, and bombings of territories and infrastructure
- The operation and maintenance of military equipment
- Construction of fortifications and defensive structures
- The passive impact of destroyed military equipment, exploded or unexploded munitions, etc.

Military support activities include:

- Production of military equipment

- Production of weapons and ammunition
- Logistical support: transportation of military equipment, weapons, ammunition, and fuel, as well as their temporary storage
- Supply of military units with ammunition, food, and other consumables

Our observations and analyses of military conflicts' consequences indicate at least three categories of environmental and anthropogenic consequences of military activity:

- Pollution and contamination of air, soil, surface and groundwater, and living organisms (primarily plants).
- Physical destruction (up to complete annihilation) of natural and human-made ecosystems and objects, as well as loss of living organisms.
- Indirect (long-term) consequences, which are not always immediately evident (see below for examples).

Environmental changes are driven by impact factors. Essentially, any of the military activities mentioned above can have environmental consequences, either directly or indirectly, with both short-term and long-term effects.

Direct consequences refer to the immediate environmental changes resulting from military activity, such as:

- Surface destruction by explosive devices (shells, bombs, mines, etc.);
- Soil, water, and air contamination from combustion products;
- Wildfires caused by military actions.

Indirect or long-term consequences arise as secondary effects of military activity. For example, after the destruction of the Kakhovka Dam, the Kakhovka Reservoir ceased to exist, causing a drop in groundwater levels in nearby settlements. Another example is the accelerated wind and water erosion of land due to craters formed by munitions explosions.

The scale, significance, and duration of the environmental impact of military activity depend on the type and intensity of the destructive factor, as well as the conditions under which the incident occurred. In many cases, the consequences—including harm to human, animal, and plant life, as well as their habitats—are severe, widespread, and long-lasting, qualifying as ecocide.

Given these circumstances, this study provides a review of published articles, reports, and data regarding the impact of Russian military aggression on air quality, land resources, water bodies, ecosystems, and biodiversity. It also includes assessments of economic and environmental damages, along with perspectives on Ukraine's post-war green recovery. Most of the reviewed papers were published before February 2025, but we do not claim that this overview reflects all publications on this topic.

January, 2025



SMOKE FROM THE FIRE
AFTER THE MISSILE ATTACK
ON KYIV, 07 SEPTEMBER
2025.

1. The Impact of Military Actions in Ukraine on Climate and Atmospheric Air

Atmospheric air, as an integral part of the natural environment, is significantly affected by military activities, and this impact is inherent in almost all forms of such activities. Even in the absence of active combat, the operation of military equipment results in significant emissions of hazardous gaseous compounds and aerosols. Military vehicles predominantly require diesel fuel, and the quality of such fuel in terms of combustion emissions has never been a priority in military operations.

For example, the estimated fuel consumption of the most widespread tank in the Russian army, the T-72, ranges from 240 litres per 100 km on a flat road to 260 litres per 100 km off-road. The tank has several fuel tanks—internal ones with a capacity of 705 litres and external ones with 500 litres. With this fuel supply, the tank can travel up to 500 km (NUOU, 2024). The fuel consumption of the T-80 tank is even higher: 450–790 litres per 100 kilometers on dry ground roads and 430–500 litres on highways. The fuel used can include diesel, gasoline, and kerosene. The number of tanks involved in combat operations on both sides reaches several tens of thousands. As of February 9, 2025, the Armed Forces of Ukraine have destroyed over 10,000 Russian tanks (Glavkom, 2025). However, this is only a fraction of the military equipment running on carbon-

based fuels. Mobile sources of greenhouse gas emissions and other hazardous substances include armoured combat vehicles, self-propelled artillery systems, multiple launch rocket systems, automotive equipment, aircraft, helicopters, and more. These numbers are suggestive of the possible scale of air pollution that can result from so many military vehicles, while the actual amount of air pollution resulting from such vehicles is currently impossible to fully assess.

Additionally, the atmosphere is polluted by combusted rocket fuel and pollutants released after explosions of shells, mines, bombs, and missiles. Fires caused by such explosions form another powerful group of pollution sources. Particularly concerning are fires resulting from attacks on oil depots and fuel storage facilities. While in the first months of the war, Ukrainian oil depots were targeted, in late 2024 and early 2025, Ukrainian armed forces' drones struck several dozen oil depots, refineries, and oil terminals in Russia, which does not contribute to clean air (BBC, 2025).

Combat actions have also caused large-scale fires in natural ecosystems, primarily forests. In March 2022 alone, over 3,200 hectares of protected forest in the Drevlyanskyi Nature Reserve were burned due to military activities (UkrInform, 2025).

Let's take a look into how the issues of the impact of military activities on atmospheric air have been covered in scientific and other publications.

1.1. Greenhouse Gas Emissions and Climate Effects Amid Increasing Militarization

In large part due to the war in Ukraine there has been a global increase in militarization, driven both by military aid and the need to strengthen national defences, particularly in NATO countries. This, in turn, results in higher production in the military-industrial complex, leading to additional greenhouse gas emissions. Military equipment production is resource- and energy-intensive, and its use on the battlefield, during training, as well as its disposal, contributes significantly to the carbon footprint.

According to estimates (Parkinson, 2022), annual greenhouse gas emissions from the military sector amount to approximately 500 MtCO₂e, which corresponds to 1% of global emissions. The global military carbon footprint over the first seven months of 2022 reached 2,750 MtCO₂e (5.5% of total emissions). The methodology used for these estimates relies on limited data, highlighting the need for military institutions to report their emissions using transparent and reliable data collection methods (CEOBS, 2022). Emission assessments should cover both combat operations and complex supply chains.

External oversight is a crucial tool for reducing military-sector emissions. In 2021, 225 organizations supported a joint call for governments to adopt concrete commitments to address this issue (CEOBS, 2021). Given the escalation of military expenditures since the full-scale war in Ukraine began, such measures have become particularly relevant.

According to estimates from De Klerk (2023), after 12 months of the full-scale war in Ukraine, greenhouse gas emissions reached 120 million tons of CO₂e. Although these emissions increased compared to the previous seven-month report, their growth rate slowed down due to limitations in frontline movements and winter conditions. Nevertheless, emissions related to combat operations remain significant and uncontrolled. The continuous fuel consumption and the extensive use of ammunition mean that countries, including Russia, Ukraine, and their allies, need to ramp up production to replenish stocks. Additionally, Russia has built kilometres of fortifications along the frontline using concrete, which has caused further carbon emissions. These factors underscore the massive impact of war on climate and global warming.

A study by Shahiqi (2023) covers a wide range of issues, including the analysis of greenhouse gas emissions, the consequences of bombings near nuclear reactors, the assessment of potential meltdown risks, and their subsequent consequences. The study also examines socio-economic aspects, the war's impact on the global market, the energy crisis, and inflation. It notes that the international community has shifted its focus from combating climate change to addressing urgent problems caused by the war in Ukraine. Part of the research is dedicated to analysing public sentiment on various issues and comparing perspectives across different groups, revealing significant discrepancies.

These factors exacerbate global climate change, complicating the implementation of the Paris Agreement's goals to limit planetary warming (IPCC, 2023). The consequences of war have long-term effects on the climate and reduce countries' ability to adapt due to infrastructure destruction and resource depletion.

The war has also had significant indirect effects on factors exacerbating climate change. A study by Oda et al. (2024) develops spatially precise assessments of greenhouse gas emissions for Ukraine, using the best available data and expert knowledge, including local expertise. Given data availability challenges, remote sensing (RS) allows for an understanding and assessment of the war's current environmental damage. The authors propose approaches to evaluate the spatial and temporal scales of sectoral emissions where possible.

Meteorological and climate consequences of military actions include changes in the physical and chemical properties of the atmosphere, increased cloud cover, acidified precipitation, occurrences of "black rain", and rising greenhouse gas emissions, which exacerbate global warming (Boychenko, 2024). Military activities cause massive pollution due to forest, land, and oil storage fires, artillery and missile strikes, and military vehicle movements.

1.2. Challenges of Conducting Hydrometeorological Monitoring in Ukraine During the War

By the end of 2023, many meteorological stations and hydrological posts in Ukraine have ceased observations or report significant data gaps due to temporary occupation and blackouts (Media Resource, 2018; Media Resource, 2022). Thus, using environmental satellite monitoring as a reliable source of information for assessing ecological conditions, especially in occupied territories, allows for remote data collection, which is critically important during active military conflicts.

1.3. Monitoring Air Pollution During the War in Ukraine

Chemical pollution from shelling and missile attacks is a significant issue (EkoDiya, 2022). Explosions produce toxic compounds such as carbon monoxide, carbon dioxide, nitrogen oxides, formaldehyde, hydrogen cyanide vapours, and others. The chemical reactions triggered by these substances cause acid rain, altering soil pH, causing burns to plants, and negatively affecting human and animal health. Metal fragments from munitions, containing sulphur, copper, and other impurities, penetrate the soil and can enter food chains. Other sources of pollution include burnt military equipment, crashed aircraft, and other remnants of combat.

An analysis of formaldehyde, aerosol, carbon monoxide, nitrogen oxide, and sulphur dioxide concentrations in the atmosphere in 2022, based on Sentinel-5P satellite data, revealed significant changes over Ukraine (Boychenko et al., 2023). Satellite observations from 2019 to 2022, processed on the Google Earth Engine platform and averaged by month and year within second-level administrative units, allowed for tracking air pollution dynamics during the war. The full-scale war in Ukraine has led to the shutdown of many industrial enterprises, which had been primary sources of emissions, especially in the eastern and southern regions. This resulted in pollutant levels in these regions dropping to background values. However, active combat, heavy shelling, military equipment usage, and fires caused significant local pollution. In some of the areas experiencing intense fighting, pollutant concentrations exceeded the 2019–2021 average levels by several times.

A study by Savenets et al., 2023, assessed air pollution changes after a year of full-scale war and analysed the concentration dynamics of nitrogen dioxide (NO₂) and carbon monoxide (CO) using TROPOMI data. Missile strikes on industrial sites, wildfires along the front line, military equipment use, and accidents significantly affected air quality. In the early months of the war, NO₂ levels declined in major cities but increased near border regions, particularly in the east and northeast. Increased CO levels were recorded during forest fires near the front line.

Savenets et al. (2023) also examined baseline atmospheric air quality before the full-scale invasion. Analysis of five pollutants (dust, sulphur dioxide (SO₂), carbon monoxide (CO), nitrogen dioxide (NO₂), and formaldehyde (CH₂O)) at 126 monitoring stations in 39

cities found that exceedances were most common for dust, NO₂, and CO. In the most polluted cities, dust and NO₂ concentrations were significantly higher than in smaller regional centers with lower industrial activity.

Research by Savenets et al. (2023) identified spatial distribution patterns of air pollution across Ukraine. Polluted air from industrial regions can spread to clean areas, including the Carpathian and Crimean Mountains, and Polissya, especially under high wind speeds. Quantitative indicators of wind speed and direction affecting pollutant concentrations in different regions were established.

An assessment of carbon monoxide (CO) content in the vertical column over the Crimean Peninsula was conducted using TROPOMI data from Sentinel-5P for the period from January 2019 to July 2023 (Maidanovych, Khlobystov, 2023). In 2022, CO levels decreased, likely due to reduced industrial and agricultural activities, and the withdrawal of some Russian troops to southern Ukraine. However, in the summer of 2023, CO concentrations increased, possibly due to natural processes, the redeployment of enemy heavy military equipment, and fires in Crimea. Agbehadji and Obagbuwa (2024) highlighted the use of computational models combining statistical methods and TROPOMI data to analyse the impact of local pollution on regional CO levels.

An air pollution index (API) analysis in Dnipro and Kamianske, based on five pollutants, was presented by Boychenko and Korol, 2024. Ground-based observations from 2009 to 2022 showed a gradual decrease in annual emissions from stationary sources since 2015–2017. Satellite data from 2019–2022 indicated stable annual concentrations of SO₂, NO₂, CO, and formaldehyde, with some monthly fluctuations. However, since August 2021, the aerosol index in the region nearly tripled.

An environmental pollution overview in Ukraine based on hydrometeorological monitoring network data is presented in UGMO (2024). In the first half of 2024, air pollution assessments were conducted in 35 cities at 120 stationary monitoring stations (Monitoring in cities like Mariupol, Lysychansk, Rubizhne, and Sievierodonetsk has ceased). Twenty-one pollutants, including eight heavy metals, were analysed. According to monitoring data, average concentrations of formaldehyde, nitrogen dioxide, and phenol exceeded daily permissible limits in most observed cities.

A study by Zalakeviciute et al., 2022, analysed the impact of war in Ukraine on air quality for five pollutants (NO₂, CO, O₃, SO₂, and PM_{2.5}) using ground-based and satellite observations. A 24.1% reduction in NO₂ levels on BAU levels was observed nationwide, with a 40.42% reduction in Kyiv in 2022. The decline in pollution is attributed to reduced anthropogenic activities due to intensified airstrikes and bombings. However, O₃ and SO₂ levels increased.

The environmental consequences of hostilities on tropospheric NO₂ levels over Ukraine from 2019 to 2022 were assessed in Malyska (2024). The study examined NO variability before the war, including the impact of COVID-19 restrictions and military actions on NO emissions. It also analysed wildfire emissions and injection heights using GFAS inventory data and livemap.ua to assess the impact of combat-related fires on atmos-

pheric pollution. Cross-border and regional air mass transport from fire sources was analysed using the HYSPLIT model (version 5.2).

Studies by Zhang et al., 2023, and Wieczorek, 2023, explored NO variations in Poland, Ukraine, and Russia in 2022, showing that fire spread and intensity significantly influence NO levels in the troposphere. The impact of military actions on fire frequency in Ukraine was also investigated.

Meng Xue (2023) used an extended detrending technique to quantify atmospheric NO₂, O₃, and PM_{2.5} changes due to emissions fluctuations caused by the pandemic and war in European cities. The study found that COVID-19 lockdowns reduced regional air pollution in Europe, but military actions led to a 9.78% increase in fine particulate matter (PM_{2.5}) and a 10.07% increase in NO₂, along with a 7.93% decrease in O₃ near combat zones. The study suggests that war-induced emissions complicated atmospheric chemical reactions, exacerbating air pollution.

Special attention should be given to the issue of air pollution caused by the destruction of oil and gas infrastructure facilities. In particular, from the first days of the full-scale invasion of Ukraine by the armed forces of the Russian Federation, primary targets included oil depots, fuel and lubricant storage facilities, and oil refineries. To assess the emissions of pollutants into the atmosphere resulting from fires at oil depots, industrial facilities, and within ecosystems due to military actions, and to calculate the extent of the damage caused, the methodology approved by the Ministry of Environmental Protection and Natural Resources of Ukraine (Міндовкілля (Ministry of Environment), 2022) is used. Risk assessments for public health related to air pollution based on this methodology are presented in (МОЗ України, (Ministry of Health), 2022). Calculations of pollutant emissions from oil depot fires based on specific case studies are presented in the works of Boychenko et al. (2025a, 2025b) and Karamushka et al. (2024, 2025).

Yatsenko (2022) identified key sources of pollutant emissions during combat operations, categorizing them into three groups: emissions from explosions and shelling of industrial sites, emissions from natural system fires, caused by military factors, and emissions from military fuel combustion. Emission estimates were based on EPA, EMEP, and other standard coefficients.

Hanoshenko et al. (2022) analyzed potential military-technogenic impacts causing severe pollution and environmental destruction. Toxic gases can form from chemical interactions between explosion products and atmospheric air, leading to the possibility of toxic carbon monoxide production. The gases produced by gunpowder explosions contain 9% CO, trinitrotoluene explosions contain 57% CO, melinite explosions contain 61% CO, and picric acid explosions contain 64% CO.

The methodology for assessing the risks to public health and damages from atmospheric air pollution is presented in (Karayeva, Varava, 2018; Міндовкілля, 2022; Ministry of Health of Ukraine, 2022). At the same time, losses from atmospheric pollution due to emissions of pollutants from the burning of petroleum products are estimated at 138.7 billion UAH, forest fires on an area of 86.7 thousand hectares caused

losses of 637.8 billion UAH (Bondar et al., 2025), but these figures are increasing as hostilities continue. Chernysh (2022) analysed the impact of military actions on air quality in Ukraine, providing evidence for damage compensation claims and recommending improved air monitoring and post-war urban air quality restoration strategies.

1.4. Impact of Fires in Natural Systems on Atmospheric Air

The analysis of the spatial and temporal spread of wild fires in the northern regions of Ukraine during the war, particularly amid active combat, missile strikes, artillery shelling, and other military actions, has been examined in the works of Бойченко 2024; Бойченко та ін. 2024; Boychenko et al., 2023, 2025a, 2025b, 2025c, 2025d; Karamushka et al., 2022, 2023, 2024, 2025; Karamushka, Kuchma et al., 2023. Satellite data (FIMS) were used for this purpose. In 2022, 2,360 fires were recorded in these regions, while in 2023, there were 495. The fires caused gas-aerosol pollution in the atmosphere of these areas. The analysis of daily fluctuations in the aerosol absorption index (AAI) in the vertical air column over the Kyiv region and the Chornobyl Exclusion Zone in 2022-2023 demonstrated that military actions increased the risk of fires and complicated their suppression.

War increases the risks of forest fire outbreaks and spreads. It has had a negative impact on the vegetation cover of affected regions. The study by Matsala et al., 2024, examined the interaction between pre-war forest management and the consequences of military actions in three of the most forested Ukrainian territories affected by the war: forests between Kharkiv and Luhansk, forests along the Dnipro Delta, and the forests of the Chornobyl Exclusion Zone. To create masks of damaged forest cover for 2022, Sentinel satellite images were used. A map was created marking forests with increased fire hazard, determined by the vulnerability of land use to fire support. These results indicate the need for ecologically balanced forest management in post-war Ukraine.

An article by Tomchenko et al., 2023, assessed changes in Ukraine's environment, particularly due to fires caused by military actions. The study provided examples of using remote sensing to detect changes in territories affected by military actions and evaluated the total number of fires in 2022. The authors proposed a methodology for obtaining daily data on fire localization in active combat zones, particularly in 15 Ukrainian regions closest to the front line. The results showed that the VIIRS spectroradiometer and the FIRMS resource are effective tools for monitoring fires and assessing environmental changes caused by them due to military actions in Ukraine.

In the study by Zibtsev et al., 2024, carbon emissions from landscape fires in Ukraine during 2022 were assessed. OroraTech forest fire monitoring technology was used to detect fires, while the perimeters of burned areas were determined using Sentinel-2 satellite imagery time series. The Copernicus Dynamic Land Cover map was used to classify the burned areas by land cover type. Carbon emissions were calculated based on fire intensity (dNBR) and the proportion of burned biomass in different land cover

types. According to the calculations, the total area affected by landscape fires in 2022 reached 749.5 thousand hectares, including 419.1 thousand hectares of arable land, 273.8 thousand hectares of other natural vegetation types, 31.1 thousand hectares of coniferous forests, and 25.5 thousand hectares of other forests. The impact of war on landscape fires is confirmed by the high proportion of fires occurring within a 60-kilometer buffer zone along the front line—68.9% of the total burned area. The study results provide critical information for assessing ecosystem service losses and carbon emissions and confirming the impact of military actions on landscape fires.

A study by Chernogor et al., 2024, calculated the energy parameters of forest and grassland fires caused by summer heat and military actions in Ukraine in 2024. Emissions of smoke, soot, and nitrogen oxides significantly exceeded background levels of these substances. The injection of polycyclic aromatic hydrocarbons exceeded background values by 570 times, while PM_{2.5} exceeded them by 14 times, and the power of acoustic radiation was 30 times higher. Emissions of CO and SO_x did not exceed several dozen percent of background values. In addition to military actions, the spread of fires in natural systems was facilitated by high air temperatures, lack of rainfall, and wind.

Short conclusions

Military actions in Ukraine have caused large-scale atmospheric pollution due to fires, shelling, the use of military equipment, and infrastructure destruction. Military activities, particularly the production and deployment of equipment, significantly increase global greenhouse gas emissions, negatively affecting climate change. Satellite and ground-based methods for monitoring atmospheric pollution are actively used to assess the war's environmental impact. However, access to data in active combat regions remains limited. General air quality changes are often difficult to determine for large areas due to meteorological influences, which create favourable conditions for pollution accumulation or dispersion. One of the priority areas is the development of monitoring systems that provide real-time assessments of natural resources in order to respond promptly to military actions and minimize environmental losses.

The most active research groups in Ukraine focused on studying and assessing the military impact on atmospheric pollution are affiliated with following academic institutes:

- The National University of “Kyiv-Mohyla Academy” (Boychenko S., Karamushka V., Kuchma T.)
- The Ukrainian Hydrometeorological Institute (Savenets M., Osadchyi V., Komisar K., Zhemera N., Oreshchenko A., Dvoretzka I.V., Kozlenko T.V., Umanets A.P., Zhemera N.S., Nadtochii L.M.)
- A leading group researching fires in Ukraine’s natural systems is the Sergii Zibtsev group from the National University of Life and Environmental Sciences of Ukraine.



CRATER AFTER THE ARRIVAL OF A ROCKET IN THE FOREST NEAR THE VILLAGE OF BUDA-BABYNESKA. KYIV REGION, 24 MAY 2024.

2. The Impact of Military Actions on Land Resources and the Geological Environment in Ukraine

2.1. Types of Impact on Land Resources and Consequences

One of the most dangerous and long-term environmental consequences of Russia's aggression against Ukraine is land contamination. The war is severely damaging one of Ukraine's main assets—its soil resources. Soil absorbs the primary impact of military actions, suffering the most contamination. As an inert component of the ecosystem, it can retain the consequences of war for a long time (Bonchkovskyi et al., 2023), leading to the destruction of the country's agricultural potential (Strokal et al., 2023).

Explosions from rockets, aerial bombs, artillery shells, heavy military equipment movement, fortification construction, landmines, and spills of fuel, lubricants, and other hazardous substances create craters, destroy soil cover and underlying rocks, pollute and compact soils, affect the aeration zone, and contaminate groundwater. Fires destroy soil biota and vegetation.

Various types of soil degradation occur simultaneously, among which the authors (Balyuk, Kucher, Soloha & Solovey, 2024) identify:

Mechanical degradation: formation of craters, soil layer mixing, destruction of soil morphology, severe compaction leading to erosion.

Physical degradation: changes in soil properties such as granulometric and aggregate composition, thermal impact, and humus layer disturbance.

Chemical degradation: contamination with toxic elements, including heavy metals, radionuclides, dioxins, and humus layer alteration due to fires and explosions.

Physico-chemical degradation: changes in soil pH and salinization.

Biological degradation: loss of soil biodiversity, sanitary condition deterioration, reduced biological activity, and impaired self-purification and humus formation processes.

2.2. Scale of Impact on Land Resources

According to maps developed by scientists at the “O.N. Sokolovsky Institute of Soil Science and Agrochemistry” (Балюк та ін., 2024) as of May 2022, the largest areas affected by hostilities were:

- Ordinary chernozems – 50.1 thousand km²
- Sod-podzolic soils – 29.4 thousand km²
- Southern chernozems – 16.2 thousand km²
- Dark chestnut soils – 9.6 thousand km².

Thus, the most affected areas are valuable chernozem soils located in combat zones, particularly in Mykolaiv, Kherson, Zaporizhzhia, Donetsk, and Luhansk regions.

In March 2023, the Institute released an updated map (Balyuk, et al. 2024) showing that around 15 million hectares of land, primarily agricultural, were affected by military actions at different times. The total area of affected land in temporarily occupied, de-occupied, and frontline areas accounts for up to 20% of Ukraine's territory. Summarized maps of damaged land are available on the institute's online portal (UGC 2024, 2024a, 2024b, 2024c).

2.3. Assessment of Impact on Land Resources

Balyuk, Kucher, & Romashchenko (2024) developed and tested a comprehensive methodology for assessing war-damaged soils, including geospatial, field, and laboratory research stages. It evaluates physical, chemical, and physico-chemical impacts of military actions on soils, tested in Kharkiv region.

Damage assessment follows the “Methodology for Determining the Damage to Soils and Lands Due to Emergencies or Armed Aggression”, approved by the Ministry of Environmental Protection and Natural Resources of Ukraine on April 4, 2022 (Order No.

167). The development of methodological foundations for damage assessment and the improvement of the approved national methodology have been addressed in various studies (Baranenko & Rusin, 2023; Didukh, 2022; Demidenko & Stakhiv, 2022; Tymchenko et al., 2024; Kucher and Kucher, 2024; Romanenko, Krysinska, & Tymchenko, 2024; Churilova & Strelnyk, 2022; Shpylova, Bendasiuk, & Lahodienko, 2023; Khomyak, 2022).

In particular, Didukh (2022) examines the issue of damage assessment using an ecosystem-based approach, where the evaluation is conducted on a point scale based on three criteria: degree of damage, resilience, and vulnerability, using urban ecosystems as an example. The study provides an example of a point-based assessment of damage to urban ecosystems resulting from military actions. However, this research does not include a mechanism for calculating the monetary cost of damages and focuses only on general principles of damage assessment.

The works of Kucher (2022) and Romanenko, Krysinska, & Tymchenko (2024) analyse the strengths and weaknesses of the national methodology and explore ways to improve it.

Kucher (2022) conducts a detailed analysis of the methodology for determining the extent of damage to soil and land caused by emergencies or armed aggression. He highlights several weaknesses, including the failure to account for lost benefits (foregone income) due to reduced soil productivity as a result of mechanical, chemical, physical, physicochemical, and biological degradation.

Other issues include insufficient justification of certain coefficients. For example, when determining the amount of damage from soil contamination, the specific costs for eliminating the consequences of soil contamination of the relevant land plot (A) are taken at 1.5, i.e. they are actually equated to one and a half times the normative monetary value of the land plot whose soils have been contaminated. However, some experts propose to apply a value of 10 for the indicator A, taking into account the special status of land as a major national asset, the danger of pollutants (heavy metals), the duration and significant cost of soil restoration measures. It means that the determination of the coefficients has weak justification base. The omission of costs associated with assessing the extent of damage and losses (such as sample collection, remote sensing, and calculations) is another issue. Therefore, Kucher (2022) provides some proposals for improving the methodology.

The collective monograph edited by Balyuk and Kucher (2015) addresses the organizational, economic, environmental, and regulatory aspects of the rational use of soil resources and soil fertility restoration, including the methodological foundations for calculating ecological and economic damages caused by soil degradation.

A study of soil contamination from missile attacks near Lviv (Petrushka et al., 2024) proposes assessing soil pollution levels using various criteria, including the contamination factor (Cf), ecological risk factor (Er), potential ecological risk index (Ri), geoaccumulation index (Igeo), and the National Iron Plus Initiative (NIPI) ecological risk coefficient.

An important step in assessing damage to soil and land resulting from armed aggression is determining the extent of contamination. This assessment is based on land plot inspections, remote sensing data, and the analysis of collected soil samples.

2.4. Remote Methods for Studying Land Resource Impact

Remote land monitoring is increasingly effective for analysing war-induced soil damage, such as craters, fires, humus layer loss, and mechanical or physical degradation (Dovhyi, Babiychuk, & Tomchenko, 2023; Osadchyi, Oreshchenko, & Savenets, 2023; Barabash, Parkhomchuk, & Shelestov, 2023; Tymchenko et al., 2024; Soloha et al., 2024).

An automated method was developed for detecting war-damaged agricultural land using free Sentinel-2 satellite data. Spectral bands with 10m resolution and vegetation indices, along with statistical indicators over time, serve as inputs for random forest classifiers. The algorithm effectively identifies damaged fields with 85% accuracy. Further anomaly detection refines damage assessment by combining spectral bands and indices (Kussul et al., 2023).

Banduryan, Kovalevskyi, Koloskov, & Lytvynenko (2023) propose infrared radiation distribution measurements with spectrometric analysis to detect pollutants beneath clean soil layers. This method delineates contamination zones without extensive sampling and may assess war-induced erosion risks.

A study using high-resolution Maxar satellite images in Chernihiv region identified 4,914 craters, 2,912 of which were in arable land, with diameters ranging from 0.5 to 13.8 meters (Bonchkovskyi et al., 2023). The study suggests classifying craters into bombing and contamination zones based on soil displacement, compaction, and pollution levels. In the bombing zone, the soil was redeposited, ejected, displaced, compacted, deformed, and heavily contaminated, whereas in the contamination zone, the soil remained mostly physically undisturbed but was slightly contaminated with explosives, shells, and bomb fragments.

Barabash, Parkhomchuk, & Shelestov (2023) propose a methodology for identifying war-damaged agricultural fields (craters, shelling marks, burned fields) by calculating NDVI index differences and spectral distribution using Sentinel-2 data.

Remote methods also help assess the war's impact on protective forest belts, crucial for soil preservation. A study (Matsala et al., 2025) found that as of 2023, 18% of protective plantings (forest shelter belts) in Ukraine's eastern agroforestry region were damaged. While total loss of agricultural protection was moderate (2.7%), local hotspots saw up to 57% losses, correlating with proximity to intense combat zones in 2022-2023.

Challenges remain in validating remote data and using it as legal evidence for soil damage assessments due to low resolution of available satellite images, subjective

interpretation in image analysis, lack of clear GIS data requirements, vegetation differences, and plant species identification difficulties via remote access.

2.5. Analysis of Soil Conditions: Sampling

Soil sampling and analysis for contaminants also present a number of challenges, particularly in interpreting and extrapolating data due to the lack of comprehensive prior soil studies, background pollutant levels in combat zones, insufficient number of accredited laboratories, variability in soil composition, climatic conditions, and anthropogenic factors having cumulative effects, among others.

Soil sampling requirements are regulated by the current standard (National Standard of Ukraine, 2019). At the same time, scientifically grounded methodological recommendations for soil sampling in combat zones have been developed (Splodytel et al., 2023). These recommendations systematize strategies and approaches for sample collection, propose a scientific-research algorithm for soil studies in combat zones, focus on studying the environmental problems caused by military impacts on soils, identify sources of pollution, and assess the impact of war on the ecological and geochemical state of soils (Shebanina et al., 2023).

2.6. Physical and Mechanical Impacts on Land Resources

Under the weight pressure from heavy machinery, normal bonds between soil particles are destroyed, disrupting their structure and altering aggregate shapes (Strokal et al., 2023). As a result, the soil becomes compacted, reducing pore volume, which directly affects soil permeability. Consequently, the amount of productive moisture in the soil decreases significantly, which limits and slows down plant growth and development, metabolic exchange, and gas cycling, increasing the likelihood of aeration-related problems.

Soil degradation due to military activities has also manifested in changes in granulometric fractions at explosion sites, burn areas, and locations contaminated with heavy metals. Studies conducted in different areas near Kharkiv, Ukraine, showed that the burning of ammunition has led to an increase in sand fraction (2.0-0.05 mm) by 1.2-1.8 times and a decrease in clay fraction (<0.002 mm) by 1.1-1.2 times (Solokha et al., 2023).

2.7. Soil Contamination with Heavy Metals

Shelling, explosions, and fires introduce manganese, chromium, arsenic, copper, nickel, zinc, cadmium, lead, and barium into the soil. Pollution from ammunition remnants is particularly concerning, as toxic metals and their alloys enter the soil in pure form or as oxides after exposure to high temperatures during explosions. These

substances are chemically stable in the natural soil environment, requiring time and abiotic and biotic processes to transition into more active forms (Agrilab, 2022).

The explosion of a single ballistic missile releases over 60 kg of toxic substances into the soil. Greaves & Hunt (2022) reported that harmful emissions typically include carbon monoxide, nitrogen dioxide, heavy metals, and solid rocket fuel residues.

Chemical soil contamination has been addressed in several studies (Splodytel et al., 2023; Kravchenko, 2015; Balyuk, Kucher, & Romashchenko, 2024; Baran, Kravchenko, Melen-Zabramna, & Shumylo-Tapiola, 2024; Zaitsev, Hryshchenko, Romanova, & Zaitseva, 2022; Chernysh et al., 2024; Havryliuk et al. 2025). However, some studies present differing results regarding contaminant distribution, composition of particularly hazardous pollutants, and their concentration levels. These discrepancies may be due to varying sampling conditions, differences in background concentrations of chemical elements in soils, and the accuracy of laboratory analyses.

Soil contamination levels with heavy metals significantly exceed hygiene standards, with the highest pollution levels recorded for Pb, Zn, and Cd (Solokha et al., 2023). Experimental data confirm that in all soil samples collected around the impact sites of X-101/X-555 cruise missiles near Lviv, concentrations of Ti, Zn, Cu, and Ni exceed permissible limits several times over (Petrushka et al., 2023).

In Kharkiv Region, cadmium contamination has increased by 200% in areas experiencing heavy shelling, in Kherson and Zaporizhzhia Regions—by 139% and 156%, respectively, along with an increase in petroleum product spills (Shebanina et al., 2023).

Soil studies conducted in the area of hostilities showed that in Dnipropetrovsk region, lead contamination exceeds the maximum permissible concentrations (MPC) by 3 times, and fluoride—by 1.5 times. In Mykolaiv region, lead levels exceed MPC by 5 times, while zinc, copper, fluoride, and petroleum product content has increased by a quarter. In Zaporizhzhia region, lead concentrations exceed MPC by 11.17 times, with zinc and fluoride increasing by half, petroleum products by 35%, and phosphates by 30% (Bulba et al., 2024).

Additionally, military actions have been found to affect the physicochemical properties of soils, including an increase in soil acidity (pH) and the density of the arable soil layer (Biyashev et al., 2023).

Elevated iron content has been recorded at the military training ground in Cherkasy region, likely linked to the use of explosives. The maximum lead content was close to the MPC, and the pH level indicated a slightly acidic soil state in training areas, potentially impacting fertility and plant growth (Shaforost et al., 2024).

In Sumy and Okhtyrka districts of Sumy region, agricultural lands in contaminated areas exhibited lead levels 5.4 times higher than background values, manganese—4.8 times, copper—4.6 times, zinc—3.9 times, cadmium—1.4 times, nickel and iron—1.2 and 1.1 times, respectively (Zaitsev et al., 2022). The highest degree of soil cover

disturbance due to military actions was observed at sites with burned military equipment. A significantly higher variation coefficient of heavy metal content was noted in combat zones compared to non-combat areas (background values), suggesting the intensity of negative impacts on soil cover.

Correlation analysis results indicate an extremely strong dependence between the content of studied heavy metal forms. However, research on the impact of bombings in Chernihiv and Sumy regions did not show clear patterns of increasing concentrations of barium, zirconium, rubidium, zinc, and vanadium compared to control plots (Datsko et al., 2024).

At sites near Novyi Korotych and Mala Rohan in Kharkiv region, increased concentrations of heavy metals (manganese, iron, cobalt, copper, cadmium, chromium, lead, and nickel) were recorded in soils of shelled areas compared to unshelled ones (Solokha et al., 2023).

A classification and assessment system for military soil degradation in terms of chemical contamination with organic and inorganic compounds was proposed for Chkalivska Territorial Community, Chuhuiv Raion, Kharkiv region (Smirnova et al., 2024). It has been established that in recently demined areas of the de-occupied territory, there is a slight increase in the content of lead (1.4 times), cobalt (1.3 times), iron (1.6 times), and zinc (2.6 times) compared to the pre-war (background) levels. Over time, a slight decrease in the content of mobile cadmium, lead, nickel, cobalt, and iron has been observed. Very low concentrations of all polycyclic aromatic hydrocarbons, explosive substances, and related nitroaromatic compounds have been detected in the studied soils.

The above-mentioned works lack data on elevated arsenic concentrations and information on the routes of contaminant entry into soils. Some information can be found in the work of Xue (2023), which graphically represents arsenic pollution of the atmosphere due to explosions, which likely reaches the soil through atmospheric precipitation. A study by Yakymchuk et al. (2024) states that arsenic is used in ammunition, paints, and electronic components of military equipment. Soil contamination with arsenic may occur due to the disposal of ammunition or the degradation of arsenic-containing materials. The author notes that arsenic content in soils affected by military actions reaches 20–50 mg/kg. Arsenic accumulation in soil can suppress plant growth, disrupt soil microbial communities, and contaminate food crops. Chronic arsenic exposure can lead to cancer, developmental abnormalities, and immune suppression in both wildlife and humans, impacting biodiversity. The challenge lies in the fact that before the full-scale invasion, contaminants such as arsenic were not given attention and were not included in the chemical analysis of Ukrainian soils.

The dynamics of metal behaviour in the soil, introduced as a result of combat actions, depend on multiple factors, including transport by flow, diffusion, root uptake by plants, adsorption/desorption, precipitation/dissolution, and soil parameters such as soil type, porosity, electrical conductivity, organic carbon content, and pH. The time

elapsed since the mechanical impact of an artillery strike also plays an important role. Numerous modelling results have shown that different heavy metals exhibit varying degrees of mobility in soil. Some metals, such as Fe, Pb, Sb, Zn, Co, and Cr, demonstrate high mobility, whereas others, such as As, Mn, Cd, Hg, V, and Cu, show lower activity. It has been found that the diffusion rate of certain heavy metals in different soil types follows a two-phase dynamic: initially, metals are released intensively, followed by a sharp decline in the release rate (Trokhymenko et al., 2023).

2.8. Impact of Unexploded Ordnance and Landmines on Land Resources

Unexploded ordnance (UXO) and landmines pose long-term risks to soil quality and land use. Their presence leads to soil contamination with explosive residues and heavy metals. Studies from Cambodia and Bosnia indicate that soils contaminated with explosive remnants exhibit altered microbial communities and impaired plant growth. The impact of UXO on the environment can be significant. UXO also hinders post-war recovery and agricultural development, leaving vast arable land areas underutilized. Moreover, the detonation of munitions releases toxic chemicals into the soil, exacerbating contamination (Didenko et al., 2024). Soil suitability for agriculture post-demining remains a subject for further research (Drobitko & Alakbarov, 2023).

2.9. Contamination of Soil and Geological Environment with Petroleum Products

Pollution from petroleum-based fuels and lubricants is one of the most widespread forms of contamination caused by military activity. This occurs due to the operation of heavy military equipment, attacks on oil industry infrastructure and industrial facilities, accidents, and other incidents. Petroleum products alter the chemical and physical properties of the soil, killing most soil flora and fauna organisms, except for the most resilient ones (Biyashev et al., 2023).

In cases of significant oil spills, infiltration into deeper geological layers and groundwater has been recorded. Detecting and studying such infiltration is a complex task that requires specialized methodological approaches. This issue is highlighted by Havryliuk et al., 2024, who propose specific methodological approaches for ecological and geological assessments of petroleum contamination in geological environments, developed based on their extensive experience. The authors of this study outline general principles for organizing and conducting field surveys, propose the types and scope of research at all assessment stages, and examine the specifics of drilling wells and performing accompanying work in petroleum-contaminated areas. Clearly, such studies will become increasingly important given the widespread occurrence of petroleum contamination hotspots in soils and geological environments, particularly in

cases of the destruction of oil depots, refineries, and terminals (Karamushka, Boychenko, & Havryliuk, 2024; Karamushka V., Derevska K., Sova., 2024).

2.10. Military Impact on Soil Biota

Explosions and the combustion of armoured vehicles have a significant impact on soil mesobiota and plants. Obtained results indicate the existence of complex interactions between various factors in the soil environment after an explosion, which significantly affect soil health. According to Solokha et al., (2023, 2024), contaminated areas have undergone changes in microbiome structure (an increase in the proportion of mycelial organisms by 20.5 times), suppression of microbiological processes (a decrease by 1.2 times), reduction of microbial biomass (decrease by 2.1 times), and high soil toxicity (99.8%).

The accumulation of heavy metals in the soil affects its fertility and microbiological activity (Zaitsev et al., 2022). In addition to heavy metals, explosives also enter the soil: 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine, octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine, nitroglycerin, nitrocellulose, 2,4-dinitrotoluene, and various perchlorate compounds used in rocket and gunpowder fuels. The use of phosphorus bombs results in the formation of phosphoric acids, phosphine, and white phosphorus particles wrapped in oxides, which can persist in the soil for years. These toxic substances interact with soil organic matter and its absorption complex, which is crucial for soil fertility (Biliavska et al., 2024).

In response to this, research has been initiated to justify diagnostic indicators for characterizing the bioactivity of soils affected by toxic substances (Biliavska et al., 2024). It has been established that the level of the repression of the microbiota in soil affected by explosions was exceptionally high compared to undamaged soil. The most sensitive were phosphate-mobilizing, nitrogen-fixing, and amylolytic (including streptomycetes) microorganisms. Pilot application of bioremediation measures by introducing microbial biomass and culture media into the soil showed promising results in restoring the main groups of soil microorganisms, which is an important indication of the potential of the bioremediation approach for further development of a comprehensive plan for restoring affected soils.

Studies on the impact of military training grounds highlight a lack of information on the impact on soil organism groups such as mites, ants, or gastropods, which play a crucial role in soil functioning (Rodríguez-Seijo et al., 2024). Data on combined effects (e.g., PTEs [potentially toxic elements such as As, Cd, Cu, Hg, Mn, Pb, Sb, Zn] + TNT and PTEs + PAHs (polycyclic aromatic hydrocarbons) are insufficient, as some studies focused on a single pollutant, usually Pb, whereas more realistic studies would investigate combined pollutants. Ecotoxicological analyses should also cover other underexplored ammunition elements such as Bi, Cu, or W. More studies are needed across different biological levels, as the impact of the same pollutant can vary for soil microorganisms, micro-, meso-, or macrofauna, and soil properties or absorption capacity affect

pollutant bioavailability. There is limited data on the combined effects of PTEs and explosive-related compounds, as most studies focus on individual contaminants. A broad spectrum of PTEs and organic pollutants should be assessed depending on the types of ammunition used and military activities. This consideration is also crucial for laboratory studies, where assessing combined effects can provide a more realistic picture than evaluating single contaminant exposure.

2.11. Soil Remediation

Significant attention is given to soil restoration research. Restoration is a crucial but highly complex task to implement. Despite numerous scientific studies (Balyuk & Kucher, 2015; Balyuk, Kucher, & Romashchenko, 2024; Datsko & Yatsenko, 2024; Petrovych, 2022; Pavelko & Baran, 2023; Kaminsky et al., 2023; Chaika, 2023), obstacles remain in implementing the proposed soil restoration approaches. The modern approach to restoring damaged soils includes comprehensive measures and is accompanied by rational soil use, application of environmentally safe technologies, sustainable agriculture practices, organic farming implementation, and the restoration of protective forest strips. Rehabilitation strategies also require significant financial resources to support ecosystem recovery and stimulate agricultural and economic restoration (Didenko et al., 2024).

or irrigated chernozems, differentiated measures for structural reclamation, removal of ammunition and weapon remnants, detoxification, agro-technical, and agro-meliorative works are proposed (Balyuk et al., 2024). Ensuring land conservation is particularly challenging if this approach is the only safe option. Equally problematic is testing proposed soil remediation methods over large areas and the subsequent disposal of contaminated biomass.

Some of the fundamental works on soil restoration come from scientists of the O. N. Sokolovsky National Scientific Center “Institute of Soil Science and Agrochemistry”, reflected in monographs (Soil Cover ..., 2023 (Ґрунтовий покрив..., 2023)); Balyuk, Kucher, & Romashchenko, 2024). It is important to consider that ecological, climatic, and other regional characteristics of Ukraine may complicate extrapolation of remediation method efficiency from one area to another, necessitating an individualized approach to soil restoration in specific physical-geographical conditions. For example, analysed works lack soil restoration measures for Mykolaiv, Kherson, and Zaporizhzhia regions, which are among the most affected by military actions.

According to Bulba et al. (2024), alongside monitoring the condition and controlling the use of fertilizers, plant protection products, and other chemicals, soil restoration requires specialized technologies and materials to restore fertility and the biological composition of the soil.

2.12. Military Impact on the Geological Environment

The environmental impacts of military actions on the geological environment are identified when they extend beyond the soil cover. Examples include crater formation, mechanical damage to rock formations, infiltration, and migration of pollutants in the aeration zone and groundwater.

A critical ecological issue is geological contamination due to the destruction of oil refineries and fuel storage facilities. For example, the destruction of an oil depot near Borodyanka led to the formation of a layer of liquid petroleum products on the groundwater surface, requiring urgent cleanup measures (Ulytskyi et al., 2023). Petrochemical contamination hotspots require complex management approaches (Shpak et al., 2023), with an essential element being mathematical modelling of processes of contamination spread and remediation actions (Mikhalchuk, 2024).

The destruction of the Kakhovka Reservoir dam caused significant negative consequences for the geological environment (Sanina & Lyuta, 2023), leading to the displacement of large amounts of accumulated sediments from the reservoir into the lower Dnipro and the Black Sea (Nasiedkin et al., 2024). The predicted erosion base change due to water level reduction in the former reservoir area will intensify surface runoff. Changes in the hydrogeological regime of groundwater (rise/fall of water levels depending on the location above or below the dam, change in groundwater flow direction) will enhance karst formation, suffusion, subsidence of loess deposits, increase flooding areas, and trigger landslides, which are widespread in the Dnipro valley (Shekhunova et al., 2024). These processes must be considered for protecting critical infrastructure and post-war recovery, as they determine soil and foundation stability (Yakovlev, 2024).

The disruption of extractive enterprises due to occupation, shelling, destruction of industrial infrastructure, and other factors has significant negative environmental consequences. The disruption of the technological cycle often leads to the flooding of mines and quarries. On the one hand, this results in the loss of mineral reserves, and on the other, it leads to groundwater contamination, as observed in the rock salt deposits of Donetsk region (Alekseenko, Stryzhak, 2023).

The indirect yet significant impact of military activities on the geological environment is evidenced by incidents involving the destruction of hydraulic structures. For example, the destruction of the Kozarovytska Dam caused the flooding of the Irpin River floodplain and a rise in groundwater levels (Khiltchevskyi, 2022), which in turn led to the flooding of the Ozerna quarry (Karamushka, Derevska, Sova, 2024). As a result, the quarry has been unsuitable for operation since March 2022.

Short conclusions

Land resources and the geological environment are among Ukraine's most valuable natural resources, and their ecological condition determines the country's potential for sustainable development. The Russian aggression has had a large-scale impact on land resources (soil cover) and the geological environment, particularly on groundwater, which is its most dynamic and vulnerable component. The consequences of the ongoing Russian aggression are colossal, and are particularly dangerous and long-lasting from an environmental perspective.

Ukrainian scientists have paid considerable attention to studying the impact of Russian aggression on soil cover. The types of impacts and consequences have been systematized, and the spatial scale of the damage has been assessed. Research efforts have also focused on soil damage assessment, particularly through the use of satellite data, which has significant practical value for improving national methodologies for evaluating damage to soil and land.

Conducting chemical analysis helped identify the main pollutants entering the soil (heavy metals, explosives), and research into their effects on soil biota has begun. Specific recommendations for the remediation of affected soils have been developed, based on sustainable farming practices, rational land use, detoxification, and agro-technical, and agro-meliorative measures.

However, research into the impact on land resources is still in its early stages. There is a need to strengthen the analytical base to identify specific pollutants entering the soil, assess their combined effects, and study soil biota, many groups of which remain unexplored. Given the scale and diversity of weaponry used by the aggressor state, it is likely that the range of detected pollutants will expand as research deepens.

More in-depth studies are required on the physical and mechanical effects of shelling and explosions on soil, which alter its structure and moisture transfer dynamics, thus limiting the potential in particular of agricultural soils.

At the same time, most research focuses on agricultural soils, while the impact on soils in natural ecosystems remains unexplored and requires further study. A crucial area of interest is understanding the link between soil pollution and degradation and biodiversity conditions in affected areas.

Contaminated soils are a potential source of groundwater pollution due to pollutant migration through soil moisture in the aeration zone. Such studies have not yet been conducted in Ukraine. They require lysimeters or the establishment of test sites, which are financially and logistically challenging. Areas of potential groundwater contamination require monitoring systems, which have not yet been implemented, even in the most intensely polluted areas, such as those affected by large-scale oil spills.

The development of remote methods for assessing land resource impacts appears promising, though these methods require validation through ground-based fieldwork.

GIS analysis of satellite data is expected to become the primary means of evaluating the spatial scale of the ongoing Russian aggression's impact on land resources.

A significant potential exists in the field of biological soil remediation, which involves introducing microbial biomass and culture media. Soil restoration is expected to be one of key priorities for future research. However, the conservation of heavily contaminated soils may be considered a potential scenario requiring scientific justification. Monitoring affected, remediated, and conserved soils will require careful scientific validation and may be used to adapt territorial management strategies.

The geological environment, given its complexity compared to soils, remains significantly less studied in the context of the consequences of the Russian aggression. Future research should primarily focus on contamination in the upper geological layers, including the aeration zone and groundwater. In addition to lysimetric studies to assess pollutant migration dynamics, research should focus on identifying and delineating so-called “hot spots” resulting from the destruction of industrial, energy, and other facilities—an area that has received little attention from researchers.

A priority should be the justification of methods for surveying contaminated areas, monitoring them, and developing remediation and management strategies. Future research should also address hazardous geological processes triggered by military actions, particularly those caused by the Kakhovka dam disaster, the destruction of other dams, and the flooding of mines and quarries. Given the environmental risks associated with improper mining operations and unauthorized resource extraction in occupied territories (such as groundwater extraction), these issues should be a subject of further research. A crucial overarching priority for all studies is the collection of evidence and scientific justification for the damage caused by Russian aggression to soils, land resources, and the geological environment.

The most active groups of researchers in Ukraine, focused on studying and assessing the military impact on land resources, soils, and the geological environment, are affiliated with the following academic institutions:

National Scientific Center “Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky” (Sviatoslav Baluk, Solokha Maksym, Vadym Solovey, Kateryna Smirnova, Lyudmyla Vorotyntseva);

Institute of Geological Sciences of the National Academy of Sciences of Ukraine (Stella Shekhunova, Tetiana Kril, Ruslan Havryliuk);

Lviv Polytechnic National University (Kucher Anatoliy);

Institute of Geochemistry, Mineralogy and Ore Formation of the National Academy of Sciences of Ukraine (Anastasiia Splodytel);

Institute of Geography, NAS of Ukraine (Oleksandr Golubtsov, Liudmyla Sorokina);

Sumy National Agrarian University (Oksana Datsko);

National University of Food Technologies (Serhii Chumachenko);

Bohdan Khmelnytsky National University of Cherkasy (Volodymyr Yatsenko, Yulia Shaforost);

Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences (Nataliia Didenko);

Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre (Maksym Matsala);

State Institution “Soils Protection Institute of Ukraine” (Yurii Zaitsev);

National Ecological Centre of Ukraine (Inna Tymchenko);

National University of Life and Environmental Sciences of Ukraine (Evgeniy Beregniak).



FOREST AFTER A FIRE THAT
BROKE OUT IN MARCH 2022.
DREVLANSKYI NATURE
RESERVE, ZHYTOMYR REGION,
02 AUGUST 2024.

3. Impact of Military Operations on Biodiversity and Natural Ecosystems in Ukraine

The Russian aggression against Ukraine since 2014 has caused significant damage to the national ecological infrastructure in eastern regions of Ukraine. However, with the onset of the full-scale Russian aggression in 2022, the scale of damage has multiplied, and the immense human suffering of the Ukrainian population has combined with the destructive impact of military operations on protected areas, natural ecosystems, and biodiversity in Ukraine. Currently, Ukraine is facing a range of unprecedented challenges in preserving nature.

In Ukraine, military actions affect biodiversity and natural ecosystems in the following ways:

- Military operations, including the movement of heavy equipment, artillery shelling, and troop movements;
- Shelling of forest plantations, artificially created phytocenoses, and natural forest ecosystems;
- Physical destruction of habitats for plant and animal species;
- The threat of unexploded ordnance;
- The mining of significant areas within protected territories;

- Construction of fortifications on protected areas and other natural systems, including setting up field infrastructure, providing heating and cooking during military operations;
- Occupation of protected areas and wetlands designated as important under the Ramsar convention;
- Destruction of the Kakhovka HPP dam.

Documenting violations, monitoring affected natural areas, studying the condition, and assessing the impact of military activity on natural systems have become one of the key areas of research by both domestic and foreign scientists.

3.1. Impact of Military Activity on Protected Areas

Ukraine's rich biodiversity and natural heritage are supported by an extensive system of protected areas and objects, including territories and objects of the nature reserve fund, their functional and protective zones, areas reserved for future protection, ecological network objects, the Emerald Network territories, Ramsar wetlands of international importance, biosphere reserves under the UNESCO "Man and the Biosphere" program, and UNESCO World Heritage sites. These territories are crucial for preserving unique ecosystems and endemic species, serving as vital objects and resources for scientific research, environmental education, and sustainable tourism.

The creation of protected areas is one of the primary and most effective methods for preserving biodiversity. Therefore, a significant amount of research focuses on the impact of military operations on the state of protected areas after 2014, especially after the full-scale Russian aggression in 2022 (Ecology. Law. Human, 2018; Strokal et al., 2023; CEOBS, 2024; Petrovych & Yamelynets, 2024; Timmins et al., 2023; Tsaryk & Kuzyk, 2022; Vasyliuk, Kolomytsev & Sapsai, 2019). It is important to note that protected areas are very sensitive to various influences and are extremely vulnerable.

The impact on protected areas is complex, leading to consequences such as:

- Physical destruction of plant and animal habitats;
- Chemical and physical contamination by explosive substances and fuel materials;
- Fires caused by shelling;
- Damage to soil and vegetation cover by heavy military vehicles, equipment, and defensive infrastructure;
- Noise and disturbance to animals, especially during the breeding season;
- The ongoing threat to animals, as well as to staff and visitors, due to mining of protected areas and the spread of unexploded ordnance;
- Damage to infrastructure of nature reserves and national parks, including the loss of equipment and documentation;
- Difficulties in conducting field research, including the loss of staff and equipment.

The impact of military actions on soils of protected areas is particularly critical as they form the basis for biodiversity, including landscape diversity, and require special management and scientifically grounded monitoring measures even in peaceful conditions.

Researchers' attention has focused on a wide range of issues, reflected, among other things, in the scientific publications listed below.

The impact of military actions had negative consequences for the state of protected areas before 2022 (CEOBS, 2024; Tsaryk & Kuzyk, 2022), including the state of forest cover in protected areas of the Emerald Network in Luhansk region, where significant negative changes were recorded from 1996 to 2020 (Shumilo et al., 2023).

Researchers have studied, among other things:

- The impact of fortification construction and outright occupation on protected areas (Strokal et al., 2023);
- The impact of military actions on the state of protected areas after 2022 (CEOBS, 2024; Timmins et al., 2023; Petrovych & Yamelynets, 2024);
- Damage to protected areas in the southern region due to the destruction of the Kakhovska HPP dam (UNEP, 2023);
- The impact of forest fires on steppe protected areas in eastern Ukraine (Vasyliuk, Kolomytsev & Sapsai, 2019);
- Assistance from community organizations to institutions of the nature reserve fund in the context of the full-scale war (Vasiliuk et al., 2024);
- The phenomenon of ecocide for biodiversity, protected territories, and natural ecosystems in Ukraine (Nikolaychuk, 2023; Sousa et al., 2022). However, in addition to the direct destructive impact on living organisms and their habitats, military activity also affects the behaviour and migration routes of migrating animals. Rusel et al., 2024, using GPS tracks and information from the Armed Conflicts Location & Event Data Project (ACLED), found in quasi experimental study that migration eagles were subjected to conflict events during their migration through Ukraine and showed different behaviour compared to previous years: they made fewer stops and deviated significantly from their previous route. This delayed their arrival at breeding sites. The study showed how military actions affect animal behaviour.

The potential of the Ramsar Convention for the effective protection of Ukraine's Ramsar wetlands during armed conflict (Wang, 2023).

3.2. Impact of Military Activity on Forests

The war has caused serious consequences for Ukraine's forests in the form of direct damage and fires caused by explosive ordnance. However, significant damage also includes large minefields, unexploded ordnance, and booby traps, which have rendered a significant portion of forest areas inaccessible for any activity.

Since forest fires destroy habitats for plants and animals and cause irreparable damage to the forest ecosystem as a whole, much of the attention of scientists has focused on studying forest fires (Strokal et al., 2023; ForestCom, 2023; Matsala et al., 2024; Vasyliuk, Kolomytsev & Sapsai, 2019; Vasyliuk, Kolomitsev & Parkhomenko, 2024).

Due to limited access, researchers are monitoring forests affected by the war using remote sensing data and assessing the impact of military actions on forest ecosystems. It is also noted that the restoration of damaged forests in the post-war period may be complicated by the current management practices that contribute to the development of forests vulnerable to climate-induced stresses.

The following publications reflect these findings:

Impact of military actions on forest ecosystems (Kuzik & Tovaryansky, 2023; Irland et al., 2023; Matsala et al., 2025).

Assessment of damage to forest protection plantations (protective belts, urban forests, ravine protection, water protection zones, and roadside protective plantings) in 2022-2023 (Matsala et al., 2025).

Interaction between pre-war forest management and the consequences of military actions (Matsala et al., 2024).

Forest management in territories contaminated by unexploded ordnance (Zibtsev et al., 2023).

Forest restoration in Ukraine during and after the war (Viter & Hubareva, 2024).

Analysis of the expected impact of the current war and post-war period on state forestry and forest resources in Ukraine (Wippel, 2023).

3.3. Impact of Military Activity on Biodiversity and Natural Ecosystems

The main consequences of the impact of military actions on biodiversity and natural ecosystems are:

- destruction of habitats for plant and animal species;
- reduction in population numbers of many species;
- death of animals and plants, including rare and endemic species;
- disruption of migration routes for animals;

- spread of invasive species;
- destruction or damage to unique ecosystems, including steppe areas, forests, and wetlands.

Researchers in this regard have studied the consequences of the destruction of the Kakhovska HPP dam for biodiversity and ecosystems, which include mass fish deaths, destruction of benthic invertebrates, threat to plant and animal populations, destruction of aquatic and coastal ecosystems, with a negative impact on ecosystem services (Andrusevych et al., 2023; UNEP, 2023); Impact of Russia's invasion of Ukraine on wild birds and their habitats (Dudkin & Harper, 2022); disruption of migration ecological corridors (Stokal et al., 2023); impact of the war on the migration of certain bird species – in particular eagles that migrate through Ukraine have shown a changed migratory pattern, stopping less and deviating from their usual routes, which interrupts their breeding (Russell et al., 2024); threat of invasive species due to the full-scale Russian invasion of Ukraine (Pashkevich N., 2023); impact of military actions on marine biodiversity and ecosystems of the Black and Azov Seas (Sadogurskaya, 2022; Tahmid et al., 2023; Minicheva et al., 2024); and the impact of the war on biodiversity outside of the regions where active combat is taking place (Hrynyk, Harbarchuk & Tiestov, 2023).

Research on the impact of military actions on biodiversity and natural ecosystems is closely linked to the assessment of environmental damage and losses caused by the war. Therefore, many researchers focus on developing methods to assess the damage to natural ecosystems during the war and determine the economic damage to Ukraine's environment (Didukh, 2022; Bezsonov, 2024; Polukarov et al., 2024; Rawtani et al., 2022). Moreover, an international register of losses caused by Russian aggression is being created and the prospects of developing compensation practices for environmental damage caused by military actions are being researched (Antonenko et al., 2022).

Various methodological approaches presented in scientific studies and official documents dedicated to assessing damage point to the existing problem of valuing ecosystems. One promising approach for solving this problem is the study of natural ecosystem services during the war and the monetary valuation of these services (Varukha, 2022; Davidson, 2019; Dzyba & Saveliev, 2023; Vasyliuk, 2023; Karamushka et al., 2025; Elbakidze et al., 2025). Research is also being conducted on the development of a legal foundation for the monetization of ecosystem services in the context of Russian armed aggression against Ukraine (Kovtun, 2024; Suetnov, 2024).

Studies that focus on the impact of the war in Ukraine on global biodiversity conservation are also important. Specifically, some researchers believe that the Russian-Ukrainian war is affecting global food systems, which may provoke a global expansion of cultivated areas and, as a result, lead to biodiversity loss far from the combat zones (Chai et al., 2024). Others argue that since maintaining peace and conserving biodiversity depend on international cooperation, codified in institutions, the war may have side effects on global biodiversity conservation due to the threat of

destruction of the existing biodiversity conservation management system at international and domestic levels (Gallo-Cajiao et al., 2023). The question of how political changes regarding global trade routes, agriculture, and energy production in response to the war in Ukraine impact the socio-economic scenarios used to set and evaluate biodiversity conservation targets is also discussed (Vincent et al., 2024). Researchers note that political responses to the war in Ukraine, particularly changes in land-use policy, currently being made in Europe in response to the invasion, threaten European biodiversity (Strange et al., 2022).

Short conclusions

The main consequences of combat actions on biodiversity and natural ecosystems include:

- **Physical disruptions:**
 - Destruction of habitats for plant and animal species;
 - Fires resulting from shelling;
 - Damage to soil and vegetation cover by heavy military vehicles, equipment, and defense infrastructure;
 - Destruction or damage to unique ecosystems, including steppe areas, forests, and wetlands;
 - Decline in the population numbers of many species;
 - Death of animals and plants, including rare and endemic species;
 - Damage to infrastructure in reserves and national parks, including loss of equipment and documentation.
- **Pollution:**
 - Chemical and physical contamination from explosives and fuels;
 - Noise and disturbance of animals, especially during the breeding period;
- **Other consequences:**
 - Disruption of animal migration paths;
 - Spread of invasive species;
 - Ongoing threat to animals as well as workers and visitors due to landmines in protected areas and the spread of unexploded ordnance;
 - Difficulty in conducting field studies, including due to the loss of personnel and equipment.

Research Gaps

The analysis of existing research shows that studies primarily focus on monitoring and examining the impact of military actions on biodiversity and natural ecosystems, as well as evaluating the damages caused by the war. Legal aspects of the impact of military actions on the environment are also considered.

At the same time, based on the analysis of collected data, certain research gaps in the study of the effects of military actions on biodiversity and natural ecosystems can be identified, including:

- Research on the connection between social and environmental problems caused by the degradation of the environment;
- Analysis of ecological, economic, and socio-political aspects of ecosystem restoration;
- Development of strategic planning principles for ecosystem restoration, sustainable forest management, and soil restoration, involving all institutions, private groups, local governments, and international support;
- Planning scenarios for the development of new ecosystems aligned with post-war societal development for areas undergoing spontaneous vegetation restoration;
- Study of the economic, infrastructural, and geopolitical consequences of the war on biodiversity and ecosystems, and its effects on health;
- Research on ecosystem services provided by different ecosystems to assess the monetary damage caused by Russia's aggression against Ukraine and justify the calculation of compensation (reparations) for the damage caused;
- Evaluation of the potential for using international and European environmental agreements for the effective protection of biodiversity and natural ecosystems during armed conflicts.

Research Priorities

It should be noted that the priorities for further research should not only be determined by identified gaps. Research that has already demonstrated its usefulness, significance, and effectiveness should continue, such as monitoring the impact of military actions on biodiversity and natural ecosystems. Based on the above and researchers' recommendations, the following research priorities can be proposed:

Continuous monitoring of the impact of military actions on biodiversity and natural ecosystems. A monitoring strategy should be developed to document both the immediate and long-term impacts of military actions on ecologically important areas, as well as remote monitoring strategies for ecologically important sites in occupied territories. To assess environmental damage, it is necessary to conduct continuous monitoring of areas affected by bombings and shelling so that their impact on the environment can be documented. Additionally, a list of priority areas (such as valuable protected natural territories) should be identified for immediate attention after the end of hostilities.

Improvement of methods for assessing damage to ecosystems caused by Russia's aggression against Ukraine. The key components of these methods should include principles for recording and documenting the inflicted damage, as well as a socio-economic assessment of the losses (including in monetary value). These methods should be based on the results of research on ecosystem services provided by various

ecosystems (forest, river, marine, steppe ecosystems, wetlands, etc.), and take into account current international practices for calculating environmental damage caused by armed conflicts, as well as international examples of compensation (reparations) for environmental harm resulting from military actions.

Development of a national ecosystem restoration strategy for Ukraine. This strategy should integrate nature-based solutions across all areas of public policy and promote rewilding – restoring highly degraded lands contaminated with unexploded ordnance. The recovery process will require coordinated and harmonized efforts from scientists and policymakers, innovation, and the application of international experience.

Development of a Sustainable Forest Management Strategy. This requires the creation of an adapted damage monitoring system based on remote sensing methods and the results of research into:

- direct and indirect damage to forest stands and forest infrastructure;
- damage to vulnerable areas and forest areas of high conservation value;
- prioritization of necessary response measures;
- potential use of timber for both industrial purposes and firewood.

The strategy should be based on an assessment of war-related damage, take into account fire risks and significant forest cover disturbances caused by military actions, include decisions for long-term monitoring of war-affected forests, use spatial analysis for post-war forest restoration planning, and define priorities for restoring forested areas.

Development of a National Soil Restoration Strategy, including within protected areas, should involve the following actions:

- demining and cleaning of soil cover. It is necessary to develop and implement national mine action standards for ecologically sensitive demining, complemented by political guidelines for prioritizing the clearance of natural ecosystems;
- rapid assessment of the impacts of combat (extent of damage, levels of contamination);
- selection of reclamation technologies based on a variety of factors;
- soil conservation in cases of catastrophic contamination;
- use of GIS technologies to study the environmental impact of the war.

Study of Spontaneous Succession in the Former Kakhovka Reservoir Area.

Research into the spontaneous regeneration of ecosystems in this territory can make a significant contribution to Ukraine's national goals in land degradation neutrality, as well as international obligations related to combating desertification.

Research on the Link Between Social and Environmental Issues Caused by Environmental Degradation. It is necessary to assess the relationship between the extent of natural ecosystem destruction and the socio-economic prospects for their

restoration, as well as the suitability of the affected areas for implementing environmentally oriented business projects.

Assessment of the Potential for Using International and European Environmental Agreements to effectively protect biodiversity and natural ecosystems during armed conflicts. This includes studying the impact of military actions on institutional networks that support environmental sustainability and efforts to conserve biodiversity and natural ecosystems.

Research on the Impact of the War in Ukraine on the International Biodiversity Conservation Governance System. Political changes related to global trade routes, agriculture, and energy production in response to the war in Ukraine may have long-term consequences for nature. Therefore, there is a need to align proposed policies with biodiversity conservation goals and to consider the potential impact of conflicts on the international biodiversity conservation governance system.

The most active groups of researchers in Ukraine focused on studying the impact of military actions on biodiversity and natural ecosystems are affiliated with the following academic institutions:

- Ukrainian Nature Conservation Group, Kyiv
- Ukraine War Environmental Consequences Work Group (UWEC WG). The website of this working group contains a database of information sources on the environmental impact of the war, including a list of organizations working in this field: <https://uwecworkgroup.info/resources/>
- National University of Life and Environmental Sciences of Ukraine, Kyiv
- M.G. Kholodny Institute of Botany of the National Academy of Sciences of Ukraine, Kyiv
- Lviv State University of Life Safety
- Conflict and Environment Observatory (CEOBS), United Kingdom
- Zoï Environment Network, NGO, Geneva
- WWF International, Gland, Switzerland & WWF Ukraine, Kyiv.



A POND CONTAMINATED WITH OIL PRODUCTS AFTER A MISSILE ATTACK ON AN OIL DEPOT. VILLAGE OF KOZHUKHIVKA, KYIV REGION, 13 SEPTEMBER 2022.

4. The Impact of Military Actions on Water Resources in Ukraine

Since the beginning of the Russian Federation’s military intervention in Ukraine, marine waters and both flowing and stagnant surface water bodies have been—and remain—targets of direct or indirect impacts of warfare, thereby acting as a kind of war victim. In some cases, water bodies have been used as a form of “weapon.” These characteristics are discussed by Gleick et al. (2023), who proposed terminology for analysing water-related conflicts (Gleick & Shimabuku 2023). This approach and classification were applied by Khilchevskyi (2022).

The characterization and assessment of the impact of military actions on Ukraine’s water bodies were reflected in the earliest scientific publications and analytical reports (UNEP 2022; Zheleznyak et al., 2022; Ladyka & Starodubtsev 2022; OECD 2022; Angurets et al. 2022; UN Ukraine 2023, 2023a; Smith & Butterworth 2023), as well as in many later publications (see, in particular, Truth Hounds 2024).

4.1. Impact of Military Activity: Water Pollution

The condition of surface water bodies in affected territories is primarily linked to the dangers of direct combat impact and combat related accidents. Moreover, in many cases, pollution risks arose due to damage to industrial enterprises and infrastructure from munitions strikes or operational failures caused by the interruption of electricity,

water, and gas supplies, or disruptions in technological processes (e.g., disruption of water treatment systems).

Pollution of water bodies is a universal feature of water-related conflicts. The risk of warfare affecting water resources is significant and often inevitable (EPL 2022). However, even in regions with a lot of heavy industry, the quality of the surface flowing water can be relatively high (Biryukov 2023; Marenkov et al. 2024).

The main threats to water bodies include chemical, organic, and biological contamination, caused by the infiltration of debris and combustion products from munitions, destruction of civilian and military equipment, damage to civil and industrial infrastructure, and other military-related environmental impacts (e.g., heavy equipment movement and fuel-lubricant leaks). These issues are widely researched (Shumilova et al. 2023; Trokhymenko et al. 2023a, 2023b; Tuchkovenko et al. 2023; Tuchkovenko & Stepanenko 2023; Truth Hounds 2024).

Ukraine's State Environmental Inspectorate registers incidents impacting natural systems, including water resources, and calculates environmental damages, including those with military causes, using methodologies developed and approved by the Ministry of Environmental Protection and Natural Resources of Ukraine (MEPNR 2022, 2022a).

Analysis (Savenko et al. 2024) shows that many water bodies changed their ecological status (particularly saprobity indices) due to large-scale combat. Pollution scale varies greatly across time and space depending on the specific factor involved. A single massive incident, the destruction of the Kakhovka Dam, caused a substantial pollution surge in the southern reaches of the Dnipro River and downstream to the Black Sea (UN Ukraine 2023). This included:

- ~150 tons of petroleum products from the destroyed hydroelectric station entering the water system and likely spreading downstream;
- waste from industrial facilities, sewage systems, fertilizer storage, and other critical infrastructure in the flooded zone;
- pollution from ~64 industrial and infrastructure sites located in or near the flood zone;
- fertilizer and chemical storage in Kherson's port zone and other potential "hotspots" (UN Ukraine 2023).

This incident also worsened water quality indicators in other regional water bodies. For example, the Inhulets River in June 2023 experienced high water levels and flooding of residential infrastructure. The main pollution sources included wastewater, destroyed livestock burial sites, and large volumes of debris washed from flooded areas (Trokhymenko et al. 2023a, 2023b).

Combat near the Dnipro reservoir cascade, i.e. the series of large reservoirs built on the Dnipro River with the now destroyed Kakhovka reservoir and dam being the southernmost, introduced new threats related to chemical, organic, and biological

pollution. These reservoirs accumulate many pollutants from their catchment areas and this phenomenon requires more in-depth research (Savenko et al., 2024).

The draining of the Kakhovka Reservoir raised valid concerns about the spread of pollutants stored in reservoir bed sediments. The reservoir had provided an important ecosystem service of water purification by depositing industrial and municipal effluents into sediments. With the drying of the lakebed and wind erosion, these accumulated pollutants posed threats to human and ecosystem health.

Several research groups studied the sediments, though many results remain unpublished or are limited in scope. A team of Czech and Ukrainian researchers analysed sediment samples from the exposed reservoir bed (Petrlik et al. 2023), identifying significant levels of pollutants such as heavy metals, Polycyclic Aromatic Hydrocarbons (PAHs), non-polar extractable compounds (NECs), hydrocarbons, polychlorinated biphenyls (PCBs), dioxins, (poly- and perfluoroalkylated substances) PFASs, and others. Some samples exceeded permissible levels. However, due to the small number and limited location of samples, conclusions cannot be generalized to the entire former reservoir area.

Marenkov et al. (2024) assessed water quality in the Dnipro Reservoir during the war, showing that while salinity indicators categorized the water as “excellent” and “very clean”, Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) exceeded norms, indicating organic pollution.

Monitoring of contamination and “hotspots” in water bodies continues. At the same time, not only hostilities, but also the occupation management of the captured territories has a very serious impact on Ukraine's water resources. In particular, the study by Boychenko et al. (2022a, 2022b) shows that the occupation of Crimea has led to a significant increase in water consumption due to intensified construction, industry, tourism, and militarization. The cessation of freshwater supplies from mainland Ukraine has worsened the situation, causing a critical drop in water levels in some reservoirs. Satellite drought index analysis from the study shows that large parts of the Crimean steppe are at moderate to high risk of drought. The study highlights that environmental vulnerability in Crimea is increasing in the steppe and coastal-steppe zones, as well as in the southern Black Sea coastal region. The mountain regions exhibit a moderate environmental condition. Climate change, unsuitable living conditions, discriminatory legal norms, inefficient management decisions by the occupying authorities, and threats to public health deepen ecological and social conflicts. The extractive environmental policy does not facilitate community adaptation to climate change, which will potentially provoke population migration to Ukraine's southern regions. According to the study, Satellite images from Sentinel-5P indicate a trend of shrinking water bodies in all studied reservoirs in Crimea compared to 2015. In 2021, the surface area of these reservoirs decreased by an average of 34%. In the Frontove, Taigan, and Mezhgirske reservoirs, the surface area shrank by more than 60%. This trend became noticeable from mid-2019 and continued until 2021. All of this data

indicates that increasing water consumption is causing depletion of natural resources and requires a balanced approach.

4.2. Impact of Military Activity: Destruction of Water Infrastructure

The second major water-related issue in conflict zones involves the environmental impact of damage to water resource management infrastructure. During fighting and drone/missile strikes, many hydrotechnical structures were damaged or destroyed. All conflict-related technological and water management infrastructure sites are marked on an interactive map (Eco-Zagroza 2023).

A list of the most notable incidents includes:

- Russian forces destroyed a temporary dam in Kherson Oblast (built in 2014 by Ukraine to block the flow of Dnipro water by canal to annexed Crimea) (Khilchevskiy 2022).
- The demolition of the dam and pumping station at the confluence of the Irpin River and the Kyiv Reservoir on the Dnipro River was carried out by the Armed Forces of Ukraine on February 26, 2022. At that time, the area was under the control of Russian forces. Due to the higher water level in the Kyiv Reservoir, water began to flood the Irpin floodplain for tens of kilometers upstream. As a result, a water barrier was created, hindering the movement of Russian military equipment during the advance on the city, which contributed to the defense of Kyiv (Khilchevskiy, 2022; Starodubtsev et al., 2022; Ladyka & Starodubtsev, 2022). However, this action also caused the flooding of significant agricultural areas and the communities of Demydiv and Kozarovychi (Elbakidze et al 2025).
- As Russian troops advanced, they destroyed urban wastewater treatment facilities in Bakhmut, Vuhledar, and others. Mykolaiv's facilities were shelled on March 9, 2022. In Mariupol, the system ran at minimal capacity due to power cuts and fighting, with untreated sewage discharged into the Sea of Azov. Other destroyed plants include those in Verkhnya Krynytsia (Zaporizhzhia Oblast), Novotroitske (Donetsk Oblast), Sievierodonetsk, Popasna, Lysychansk, Rubizhne, Druzhkivka, and Velyko-Anadol station (UNEP 2022; Angurets et al. 2022).
- The Oskil Reservoir dam sustained repeated attacks in 2022 and was reported by State Environmental Inspection to be destroyed on March 13, 2022 (Kolodezhna & Vasyliuk 2022; Ladyka & Starodubtsev 2022).
- On June 11, 2023, Russian forces blew up a dam on the Mokri Yaly River near Novodarivka (Zaporizhzhia-Donetsk border), flooding areas on both riverbanks (BBC News 2023). On June 6, 2023, the Russian military detonated the Kakhovka Dam – one of the most devastating acts of aggression and one of Europe's largest man-made disasters in a century. Its long-term economic, social, and ecological consequences extend far beyond Ukraine (Afanasyev 2023; Eco-Zagroza 2023; Gleick et al. 2023; Риженко 2023; UN Ukraine 2023; Vyshnevskiy et al. 2023; Vyshnevskiy & Shevchuk, 2024). This catastrophe attracted the attention of a

significant number of researchers and policymakers and became one of the most pressing topics.

- A missile strike in September 2022 damaged the Karachunivska Dam near Kryvyi Rih, causing the Inhulets River to overflow (Meduza 2022; BBC News 2023).
- On March 22, 2024, Russia launched 20 missile strikes on Zaporizhzhia, targeting the Dnipro Hydroelectric Station. Though the dam held, the turbine hall and electrical systems were destroyed (TCH 2022; BBC News 2023).

4.3. The International Dimension of the War's Impact on Water Resources

Khilchevskiy (2022) examines water-related conflicts in Ukraine in the context of the international classification developed by the Pacific Institute. This classification identifies three types of water conflicts. *Water as a trigger* – when water is the root cause of conflict, typically involving disputes over control of a water body that escalate into violence. *Water as a weapon* – when a water resource is used as a tool or weapon during violent conflict. *Water as a casualty* – when a water system becomes the target of intentional or accidental violence. Similar ideas had previously been proposed by Gleick et al. (2023), and this framework is used to analyse the impacts of military action on Ukraine's water resources.

The scale of certain incidents, especially the Kakhovka disaster, has had significant environmental repercussions that extend far beyond Ukraine's borders (Kosova, 2023). Investigating these incidents and their consequences forms the basis for planning the recovery of war-affected territories, including the restoration of ecosystems and natural resources. The practical importance of such research lies in its contribution to understanding the scope of the environmental problems caused by the war and in developing effective measures to address them (Shahini et al., 2024).

4.4. Economic and Social Consequences

Ukraine has lost nearly one-third of its accumulated freshwater reserves (approximately 19 km³) valued at over 18 billion USD. Damage to canals, pipelines, pumping stations, and water supply systems has left more than five million people without access to drinking water (Hapich & Onopriienko, 2024; Hapich et al., 2024). The disruption of water supply resulting from the destruction of the Kakhovka Hydropower Plant alone affected more than one million people. However, the long-term socio-economic impact of this incident could affect up to 1.5 million people in the south eastern macro-regions of the country (ACAPS, 2023).

A concise overview of the losses in energy, agriculture (irrigation and bio-resources), logistics, infrastructure, industry, and the social sector caused by the destruction of the Kakhovka dam is provided in the publication by CES (2023), current as of June 9, 2023.

4.5. The Kakhovka Disaster

The destruction of the Kakhovka dam on June 6, 2023, stands as one of the most devastating crimes committed by Russian aggressors, causing loss of life and catastrophic consequences for communities, industrial infrastructure, natural systems, and agriculture in the region (UN Ukraine, 2023; Vyshnevskiy et al., 2023; Afanasiev, 2023; CEOBS, 2023; UNEP, 2023; ACAPS, 2023; Stone 2024). As such, this horrific incident and its consequences have become, and will likely long remain, a subject of close scrutiny by researchers, policymakers, journalists, civil society organizations, and international institutions.

Notably, journalists and international organizations have documented the chronology of the attack (Ryzhenko, 2023) and tracked its consequences from the moment it occurred (Smith & Butterworth, 2023; Naddaf, 2023; Truth Hounds, 2024; CEOBS, 2023), assessing it as an unjustifiable act of terrorism (Ryzhenko, 2023). Hundreds of media and social media reports make comprehensive analysis difficult, but certain generalizations are possible.

The environmental consequences of the Kakhovka disaster for the ecosystems of the Kakhovka Reservoir and the Lower Dnipro, as well as the ecological, economic, and social losses, have become the subject of numerous studies and analyses (Stokstad, 2023a, 2023b; NASU, 2023a, 2023b; Naddaf, 2023).

4.5.1 Dynamics of the Destruction of the Kakhovka Reservoir

Numerous publications have documented the dynamics of the destruction of the Kakhovka Reservoir. Ukraine's Ministry of Environmental Protection regularly monitored and published updates on the status and development of the situation in the reservoir zone (see, for example, Eco-Zagroza, 2023).

Researchers from the Ukrainian Hydrometeorological Institute (NASU, 2023, 2023a, 2023b, 2023c) systematically tracked the reservoir's condition after the dam was blown up, and other researchers also provided detailed descriptions (Magas et al., 2023). As of June 20, 2023, the reservoir had lost 10 meters of depth (NASU, 2023a). By June 18, 2023, researchers reported that the reservoir had effectively ceased to exist (NASU, 2023b).

Two months after the dam's destruction, the surface area of the Dnipro's riverbed water was about 120 km² (only 5.5% of the reservoir's total volume), while isolated shallow water bodies covered approximately 307 km², though this area continued to shrink due to evaporation and drainage (Novitskyi et al., 2024).

4.5.2 Impact on Regional Water Supply

The destruction of the Kakhovka Hydropower Plant disrupted water supply for the population, agricultural sector, and industry in the region, affecting more than one million people. Given the ongoing occupation of the left bank of the Kakhovka Reservoir and active hostilities, the socio-economic impact on south eastern regions of Ukraine is

expected to be long-term, with up to 1.5 million people affected (ACAPS, 2023). Other authors provide even higher estimates. According to Hapich et al. (2024), Ukraine lost nearly one-third of its accumulated freshwater reserves (approximately 19 km³), valued at over 18 billion USD. Damage to canals, pipelines, pumping stations, and water supply systems left more than 5 million people without access to drinking water.

The loss of hydrostatic pressure in the Kakhovka Reservoir altered groundwater storage and flow, as well as surface water dynamics and intake structures – further disrupting water supply for people living in nearby areas.

The dam's destruction halted water distribution to southern Ukraine and Crimea, impacting 750,000 hectares of irrigated agricultural land (Hapich & Onopriienko, 2024). As a result, several publications analyse alternative water supply solutions. Sanina & Liuta (2023), while assessing the loss of water supply capabilities, examined the availability of forecasted resources and operational reserves of potable-quality groundwater in the region. They showed that the region (particularly Kherson Oblast) possesses significant reserves of groundwater, which could be used as a primary source of drinking water. However, full-scale implementation of such measures will only be possible after the region is liberated. Issues of water supply are also discussed in detail by Hapich et al. (2024).

4.5.3 Impact on Biodiversity and Ecosystems of Flooded Areas

The consequences of the Russian terrorist attack on the Kakhovka HPP for wildlife have been analyzed by the Ukrainian Nature Conservation Group (Moisiienko et al., 2023; Kuzemko et al., 2023) and other research teams.

Assessments have revealed devastating impacts. Approximately 80,000 hectares of protected areas, including the Lower Dnipro National Nature Park and the Askania-Nova Biosphere Reserve, were threatened or damaged. Most of the Lower Dnipro National Park was flooded (UN Ukraine, 2023). The destruction of the Kakhovka dam was catastrophic for aquatic organisms, including 42 species of fish, 20 of which are commercially important. Mass fish die-offs were observed throughout the drained reservoir (State Fisheries Agency of Ukraine, 2023).

Notably, the destruction of dams and reservoirs on other rivers—such as the Oskil River—also caused significant losses. According to Suspilne Kharkiv (2022), nearly 2 million fish died in the Oskil Reservoir (Kharkiv region) during the spawning season, following a water release caused by the destruction of the dam by Russian occupation forces in March 2022.

Fishing and fish sales from the Kakhovka Reservoir accounted for 22% of Ukraine's freshwater fish market. Over 11,000 tonnes of fish were lost within days, while losses from commercial fish catch are estimated at 2,585 tonnes, valued at up to 5.4 million USD annually (Novitskyi et al., 2024). Nearly all spawning and feeding grounds were destroyed; damage to infrastructure, amounting to about 270 million USD, must be repaired to restore fisheries' ecosystem services (Novitskyi et al., 2024). In fact, the

reservoir's ecosystem service of fish production has been lost in the region (Karamushka & Adamenko, 2023; Karamushka et al., 2025).

Just a month after the reservoir bed was drained, vegetation began to grow rapidly (Kuzemko et al., 2023; Ukrainian Nature Conservation Group, 2023). The Ukrainian Nature Conservation Group continues remote sensing and field research. Already in the first year after the catastrophe, a young forest has been growing on the site of the former reservoir (Moisiienko, 2023; Vasyliuk et al., 2023; Vasyliuk et al., 2025; Suspilne Zaporizhzhia, 2024).

4.5.4 Impact on the Black Sea Ecosystem

Following the destruction of the Kakhovka Dam, 14 cubic kilometers of water from the Kakhovka Reservoir surged into the Black Sea, flooding vast areas of the left bank of the Kherson region and the lower Dnipro River. Thousands of tons of pollutants from the inundated territories entered the Black Sea over the following weeks, causing severe ecological consequences for the marine ecosystem in the region (Vyshnevskiy et al., 2023; Minicheva et al., 2023; Tuchkovenko et al., 2023, 2024; Tuchkovenko & Stepanenko, 2023).

Expeditionary research conducted by the Institute of Marine Biology took place from June to August 2023 at 11 coastal stations ranging from the village of Koblevo to Cape Velykyi Fontan. The study analysed hydrological and hydrochemical parameters, water toxicity, the condition of biotic communities (microsammon, meiobenthos, macrozoobenthos, phytobenthos, phytoplankton, zooplankton), aquatic biological resources, and chlorophyll-a concentration dynamic. This allowed researchers to assess the scale of the ecosystem's response to the influx of Kakhovka reservoir water into the sea. Anomalies were identified in both abiotic and biotic components (calculated as the percentage deviation of the indicator values in June-August 2023 from regional norms for the same period).

The “explosive” impact phase lasted about three months from the onset of the disaster on June 6, 2023. By August 2023, most parameters had returned to average regional levels. The inflow of polluted waters from the Kakhovka Reservoir into the marine ecosystem caused desalination along the Odesa coastline down to 3.95‰ (10 - 17‰ under normal conditions), reduced surface oxygen saturation to below 75%, increased ammonium nitrogen concentration up to 13.8 MAC (Maximum Allowable Concentrations), and triggered acute lethal toxicity. There was also a marked increase in chlorophyll-a concentrations and a mass bloom of cyanobacterial (blue-green algae) plankton.

Benthic communities experienced inhibited macroalgal development, abnormal macrophyte surface index values, and significant changes in the structure of fouling zoocommunities. Notable events included the death of freshwater fish species that entered the sea and the mass mortality of Black Sea mussels, amounting to approximately 3,700 tons of biomass.

The authors identified four stages of the initial three-month “explosive” phase:

- Stage I (June 6–11): Hydrological/-hydrochemical and physical pulse impacts, with major anomalies in river discharge and salinity reduction.
- Stage II (June 12–July 10): Explosive biotic response, particularly acute in phyto- and zoocomponents.
- Stage III (July 11–August 10): High levels of production-destruction processes.
- Stage IV (August 11–31): Return to regional baseline conditions (Minicheva et al., 2023).

Monitoring of the Black Sea coastline from Koblevo to Cape Velykyi Fontan is ongoing.

Tuchkovenko et al. (2024) presented the results of numerical mathematical modelling of the dispersion of transformed and polluted Dnipro River waters in the northwestern Black Sea, following the artificial mega flood caused by Russian forces destroying the Kakhovka Dam in June 2023. The floodwaters carried various pollutants from the Kakhovka Reservoir, the Dnipro delta, bottom sediments, and the flooded territories. Special attention was given to changes in oceanographic conditions in the Dnipro-Buh Estuary (DBE), which determine the scale of marine environmental contamination.

Safranov et al. (2024) examined groups of ecosystem services and the factors influencing their utilization. Due to military activity, the use of the resource component of ecosystem services has been reduced to a minimum. Combat operations have virtually halted recreational and wellness services in the coastal areas of the North western Black Sea region.

4.5.5. Future of the Kakhovka Dam and Reservoir

Debates over the prospects and necessity of restoring the destroyed Kakhovka Hydroelectric Power Station began almost immediately after the dam’s destruction (Vasyliuk et al., 2023). The dam's collapse and the draining of the reservoir stopped irrigation, industrial, and drinking water supplies for southern Ukraine – water that is critically needed for the region's development. As a result, some experts support at least partial restoration of the dam and reservoir. Given adjustments in water intake and changes in hydrological regimes caused by climate change, the normal and maximum levels of the reservoir could be lowered (Vyshnevskyi et al., 2023; Vyshnevskyi & Shevchuk, 2024).

Others, mainly academics, argue that the public discourse has pushed the narrative of restoration as the only solution to the socio-economic problems caused by the dam’s destruction. They highlight existing environmental concerns and the potential consequences of re-flooding the reservoir (Vasyliuk et al., 2023).

The decision by the Cabinet of Ministers of Ukraine (CMU 2023) brought the discussion into the practical realm. The CMU approved a reconstruction project for the Kakhovka HPP, primarily to ensure the effective functioning of the Dnipro HPP located in Zaporizhzhia. However, the project remains unrealized with an uncertain future, as

even conducting loss assessments is currently unfeasible due to widespread landmines and ongoing hostilities (Stokstad, 2023).

Short conclusions

Research into the impact of military activity on Ukraine’s water resources is ongoing and will likely continue until the hot phase of the armed conflict ends. This war, in which Ukraine defends its right to exist and develop on its internationally recognized territory, has caused widespread destruction of water bodies—both as casualties and as instruments of warfare.

Even after active hostilities cease, research will remain essential. Priority areas include:

Damage assessment in economic and ecological terms resulting from enemy military actions on Ukraine’s water resources.

Monitoring studies of “hotspots” affected by combat incidents. One key area remains the drained Kakhovka Reservoir, where a new wetland ecosystem is spontaneously emerging with minimal human intervention.

Practical research into the restoration and rehabilitation of affected water bodies, focusing on developing or adapting best practices for pollution clean-up and ecosystem recovery.

Development of sustainable water management approaches and technologies to ensure a reliable water supply for populations and the economy.

Local communities may have different priorities, but these directions are expected to dominate the national research agenda.

Key research groups focusing on the impact of warfare on aquatic resources and ecosystems:

- Institute of Hydrobiology, NAS of Ukraine, Kyiv (Serhii Afanasiev and others)
- Ukrainian Hydrometeorological Institute, SES and NAS of Ukraine (Volodymyr Osadchyi and others)
- Institute of Marine Biology, NAS of Ukraine (Halyna Minicheva, Yurii Tuchkovenko and others)
- Taras Shevchenko National University of Kyiv (Valentyn Khilchevskyi and others)
- Institute of Geography, NAS of Ukraine, Kyiv
- National University of Life and Environmental Sciences of Ukraine (Maryna Ladyka, Volodymyr Starodubtsev and others)
- National Aviation University, Kyiv (Viktor Vyshnevskyi and others)
- Faculty of Water Management Engineering and Ecology, Dnipro State Agrarian and Economic University (Roman Novitskyi, Hennadii Hapich and others)
- Oles Honchar Dnipro National University (Oleh Marenkov and others)

- Ukrainian Scientific Center of Ecology of the Sea (UkrSCES) (Viktor Komorin and others)
- National University of Kyiv-Mohyla Academy, Kyiv (Viktor Karamushka and others)
- Institute of Water Problems and Land Reclamation (Serhii Shevchuk and others)
- Ukrainian Nature Conservation Group / Institute of Botany, NAS of Ukraine (Oleksii Vasyliuk, Ivan Moisiienko, Oleksandr Khodosovtsev, Anna Kuzemko and others)
- Admiral Makarov National University of Shipbuilding (Hanna Trokhymenko, Nataliia Magas and others)
- Odesa State Environmental University (Yurii Tuchkovenko, Serhii Stepanenko, Tamerlan Safarov and others)
- Conflict and Environment Observatory (CEOBS), UK
- Zoï Environment Network, NGO, Geneva
- WWF International, Gland, Switzerland & WWF Ukraine, Kyiv
- Pacific Institute, USA (Peter Gleick and others)



CRATER FROM A ROCKET
EXPLOSION ON A PLAYGROUND.
KYIV, SHEVCHENKO PARK,
15 OCTOBER 2025.

5. Assessment of Environmental Losses and Damages Caused by Military Actions in Ukraine

The ongoing military aggression of the Russian Federation against Ukraine has caused significant environmental losses and damages, which require careful monetary assessment. Monetary valuation is one of the most common approaches (Christie et al., 2012), as it is often considered the most effective language for communication with political and business institutions. However, this task is complex, as the environmental degradation caused by military actions is multifaceted, and the methodologies and approaches for its assessment require considerable resources and time for calculations.

This analytical work reviews existing methodological approaches and conducts assessments of environmental losses and damages caused by military actions in Ukraine. The information search was conducted in open scientific databases using key terms related to the research topic, focusing on four types of environmental damage: air pollution, impact on water bodies, agriculture, and natural ecosystems and protected areas.

The analysis revealed that the assessment of environmental damage caused by the war in Ukraine faces significant methodological discrepancies, complicating the alignment of results between Ukrainian and international approaches. In light of this, the work begins with an analysis of existing assessment approaches that will serve as a basis for further considerations.

5.1. Methodological Approaches to Assessing Losses and Damages

Verstyak (2023) outlines the main methodologies and mechanisms for assessing the monetary losses from environmental damage used by the Working Group at the Operational Headquarters of the State Ecological Inspectorate. The author also proposes forms and methods for evaluating the environmental damage caused by the Russian Federation's war against Ukraine. In our review, we have partially borrowed Verstyak's approach to describe the methodologies for the monetary valuation of environmental losses and damages caused by military actions in Ukraine.

5.2. National Regulatory and Legal Framework for Damage Assessment

This section relies on the Cabinet of Ministers of Ukraine Resolution No. 326 of March 20, 2022, which defines the procedures for assessing damage and losses caused to Ukraine as a result of armed aggression (CMU, 2022). The document outlines the primary directions of damage assessment, including human, military, economic, as well as harm caused to forests, land, and housing stock. The resolution also requires relevant ministries and state bodies to develop methodologies for assessing the damage based on its types.

The Ministry of Environmental Protection and Natural Resources of Ukraine (Ministry of Environmental Protection) is involved in collecting data on environmental threats caused by military actions and has developed several regulatory protocols that regulate the procedures for determining damage in various spheres of natural resource management (DEI, 2022a). Annex 1 contains a list of these documents.

According to the assessment of environmental damage caused between February 24, 2022, and September 13, 2024, the total loss amounts to \$62.9 billion USD. The largest losses are recorded in the area of land resources—\$27.9 billion. Damage to the atmosphere is valued at \$17.7 billion, to nature reserves—\$15.2 billion, and to water resources—\$2.1 billion (Top Lead, 2024). According to the Ministry of Environmental Protection, by the end of 2024, the total amount of damage reached \$71 billion USD (Ministry of Environmental Protection, 2024).

At the same time, a complete assessment of the damage can only be made after the end of the fighting, the de-occupation of seized regions, and the completion of mine-clearing of land. According to Deputy Minister of Environmental Protection and Natural

Resources of Ukraine Olena Kramarenko, this process may take several decades (Ukrinform, 2023).

5.3. International Initiatives

International initiatives and projects aimed at assessing war-related damage use standardized approaches to analyse losses in various sectors, such as ecology, social affairs, and the economy. One of the key methodologies is the “Rapid Damage and Needs Assessment” (RDNA), implemented by international organizations in collaboration with the Government of Ukraine (World Bank, 2022). RDNA covers a wide range of sectors, including infrastructure, economy, social affairs, and the environment, accounting for both direct losses and indirect consequences. The methodology is based on satellite data analysis, field studies, expert consultations, and the collection of information from local and international organizations. The main focus is on assessing the cost of infrastructure, ecosystem, and humanitarian needs recovery, using internationally recognized standards to attract international aid.

According to the World Bank’s assessment in 2024, the total losses in the forestry sector, including burned areas, air pollution, and damage to protected areas due to the destruction of the Kakhovka dam, amount to \$26.5 billion USD (World Bank, 2024). This is several times higher than previous RDNA2 estimates, which were only \$523 million and included losses due to reduced carbon absorption by forests. The main reasons for the increase are the 16% increase in burned forest area and the addition of new categories of losses, including air pollution (\$9.9 billion), ecosystem service losses due to the Kakhovka dam destruction (\$9.6 billion), and losses of services from other natural landscapes (\$6.5 billion).

Another important document is the UN report “Post Disaster Needs Assessment of the Kakhovka Hydroelectric Power Station”, prepared jointly by the Government of Ukraine and the United Nations in 2023 (UN, 2023). This report also applies the standardized Post-Disaster Needs Assessment PDNA methodology to assess damage and define priority recovery measures for affected areas.

5.4. Independent Assessments by Research Centers and Foundations

This direction includes independent assessments conducted by research centers, universities, and foundations that provide an objective analysis of damages and create an evidence base for submission to international courts. Methods for assessing the monetary losses from environmental damage take into account ecosystem degradation, environmental pollution, and other environmental consequences of the war.

Among them are works by national university scholars regarding damage assessments for forests (Soloviy, 2022) and agriculture (Tretyak, 2024), listed below. Academician

Didukh, from the first days of the full-scale invasion, proposed an ecosystem approach to assessing environmental damage (Didukh, 2022). Under his leadership, staff from the M.G. Kholodny Institute of Botany of the National Academy of Sciences of Ukraine are conducting studies, which are described in the section on nature reserves.

5.5. Air Pollution Impact Assessments

The only available data on the impact of air pollution from fires is provided in the third report “Rapid Damage and Needs Assessment” – RDNA3 (World Bank, 2024). Emission volumes were determined according to technical guidance for preparing national emission inventories (EEP/EEA recommendations), multiplied by coefficients that account for danger, environmental impact, and the scale of the event, as well as the unit cost corresponding to the tax rate on emissions from stationary sources (order of April 13, 2022, No. 175 and Article 143 of the Tax Code (Ministry of Environmental Protection, 2022b)).

According to estimates, losses from air pollution due to burning of natural systems (primarily forests) in the region of the Kakhovka HPP are valued at \$9.9 billion USD, indicating the significant impact of this factor on the ecological and economic situation in the region. This category accounts for 37% of the total losses in the forestry sector, which amounted to \$26.5 billion USD (World Bank, 2024).

A group of scientists with support from the Ministry of Environmental Protection and the NGO “EcoAction” conducted calculations of greenhouse gas emissions for the 24 months caused by the Russian invasion. It was established that emissions amounted to 175 million tons of CO₂, and the total climate damage amounted to over \$32 billion USD (De Clerk et al., 2024). To assess the monetary value, the Social Cost of Carbon (SCC) was used as a basis. The SCC measures the present value of an additional unit of carbon (or an equivalent volume of other greenhouse gases) emitted today, by summing up the total global cost of the damage it causes over its entire atmospheric lifecycle. The SCC used by the authors was based on the American EPA and publications in the journal *Nature* (Rennert, 2022) – \$185 USD per ton of CO₂.

5.6. Assessments of the Impact on Natural Resources

The destruction of the Kakhovka HPP caused significant ecological-economic damage in various sectors. Didkovska (2023) summarized data on environmental damage assessment based on information provided by the Ministry of Agrarian Policy of Ukraine, the Ministry of Environmental Protection of Ukraine, and the State Ecological Inspectorate, covering the main areas. These sums were obtained based on approved methodologies by relevant ministries according to Resolution No. 326 (CMU, 2022).

Environment: The total environmental damage, including the loss of protected areas and forest plantations, amounts to 55.6 billion UAH.

Water Resources: Spills of machine oil and other harmful substances into water resources, as well as partial erosion of vegetation, mollusks, and general water pollution, caused damage of 2 billion UAH.

Bioresources: Mass fish die-off caused by the catastrophe is valued at 10.5 billion UAH.

Land Resources: Damaged by flooding, salinization, and soil compaction. Additionally, irrigated lands may be affected by desertification.

Hydromelioration Sector: Destruction and damage to meliorative infrastructure, including canals, is estimated at 150-160 million UAH.

Agriculture: The total losses in agriculture due to the lack of irrigation amount to \$1.5 billion USD per year, which corresponds to the value of agricultural products grown on irrigated land. Agricultural sector losses from flooding of lands are estimated at 3-5 billion UAH.

The UN report “Post Disaster Needs Assessment of the Kakhovka HPP” for 2023, jointly prepared by the Government of Ukraine and the United Nations using the UN PDNA methodology, estimates ecosystem service losses at \$11.3 billion (UN, 2023). The specific methodology is not disclosed in the report, so it is difficult to discuss the thoroughness of the assessment of ecosystem service losses.

Tretyak and co-authors (Tretyak et al., 2024) calculated the damage from soil pollution with petroleum products using a methodology approved by the Ministry of Environmental Protection Order No. 167 dated 04.04.2022 (Ministry of Environment, 2022a) for an agricultural land plot within the ecological network of a territorial community in Kyiv region. It was shown that for 1 hectare of land polluted by petroleum products, the damage would amount to 506,000 UAH.

It is noteworthy that the authors applied another methodology for the same plot, approved by the Cabinet of Ministers of Ukraine in 1997 (Cabinet of Ministers of Ukraine, 1997), according to which as of December 18, 2023, the norm for arable land in Kyiv region is 2,362,000 UAH/ha, which is 4.66 times higher than the damage calculated according to the Ministry of Environment’s methodology.

According to Tretyak et al., 2024, the methodology approved by Order No. 167 needs improvement. They proposed a methodological approach for assessing damage to land resources affected by military actions, based on the 1997 methodology with indexed standards. They calculated the weighted average standard for agricultural lands across each region of Ukraine and estimated that the damage caused to land in use due to military actions amounts to 15,683.0 billion UAH or 423.6 billion USD.

Olishevskiy (2024) also concludes that the existing methodologies of the Ministry of Environment and the Ministry of Agrarian Policy are not fully tested and require significant specific data on land plots, which demands additional financial resources and time, complicating the use of these methodologies for rapid calculations (Olishevskiy, 2024). Instead, he suggests using normative monetary evaluation (NME) as

the basis for expert assessment of the damage to land plots damaged as a result of Russian aggression. The NME of a land plot, according to the current regulations (Cabinet of Ministers of Ukraine, 2021), includes the following factors: the norm of capitalized rent income, the area of the land plot, the location of the territorial community within the influence zone of large cities, the recreational value of settlements, the location of the territory within radiation contamination zones, zonal factors, the intended use of the land plot, its use according to the land category, and the indexation of NME from the time of approval of the standard to the moment of evaluation.

The author conducted calculations for the Bucha territorial community and demonstrated how damage, determined based on normative monetary evaluation, provides a basis for estimating losses and planning restoration measures for agricultural land.

5.7. Impact assessment on natural ecosystems and protected areas

Soloviy I. and his colleagues from the Lviv National Forestry and Technical University of Ukraine proposed modern approaches to assessing the value of forest ecosystem services within protected natural areas even before the full-scale invasion (Soloviy, 2022). He considers the assessment of ecosystem services in the context of introducing a payment system, which implies financial incentives for ecosystem conservation. The authors proposed an eight-stage assessment methodology, considering limited resources and providing for an interdisciplinary approach. The main conclusion is the importance of integrating ecosystem service assessments into the management system of Ukraine's protected natural areas, which will facilitate the use of these values in regulatory and economic instruments of environmental policy.

The M.G. Kholodny Institute of Botany of the National Academy of Sciences of Ukraine has developed a scheme of logistical operations for studying and assessing the damage caused to ecosystems, aiming to receive reparations and prevent further negative consequences (Didukh, 2023). The scheme includes four key stages:

Stage I: Data documentation. This stage involves recording ecosystem violations using remote sensing materials, photographs, forest taxation data, and other sources. Particular attention is given to creating a database with the ability to integrate it into the State Land Cadastre.

Stage II: Identification of habitats and damage size. At this stage, the degree of disruption and the scale of the loss of valuable biodiversity components are assessed. Damage is evaluated using a scoring system, allowing the determination of their ecological impact.

Stage III: Monetary damage assessment. This stage involves calculating direct and indirect damages in monetary and energy equivalents. The assessment is based on

determining the value of ecosystem services, restoration costs to a corresponding state, and additional reclamation measures. This ensures the preparation of reliable reparations claims.

Stage IV: Development of measures to minimize consequences. The final stage involves developing proposals to reduce negative impacts and restore ecosystems. This requires field studies in natural conditions, which will enable the creation of practical recommendations for restoration.

For the third stage, international methodologies such as The Economics of Ecosystems and Biodiversity (TEEB), Common International Classification of Ecosystem Services (CICES), and disaster and recovery assessment from the US Federal Emergency Management Agency (FEMA-2022) were used, but adjustments were made to accommodate Ukrainian realities. Specifically, Y. Didukh outlines three approaches to calculating the monetary equivalents of environmental damage:

The first is based on the value of resources and is typically used by economists.

The second takes into account carbon, energy, or conventional fuel indicators (e.g., barrels of oil) and is used by ecologists for assessing regulatory and supporting ecosystem services.

The third considers cost substitution (supporting and socio-information services) and is used by both economists and ecologists.

However, Y. Didukh emphasizes that for some services, such as the scientific value of habitats or the loss of rare species, such calculations are impossible, although their value is recognized.

Scientists calculated the damage to the “Zalissya” National Nature Park caused by shelling and the creation of craters. According to the calculations, the damage to forests is \$248,250, but with ecosystem services and restoration costs over 70 years, the amount increases to \$695,110 (Didukh, 2023).

The researchers compared the results with estimates made using other methodologies. For example, using the damage tax rates established by the State Forestry Agency, the damage is estimated at \$44,300. The i-Tree Eco methodology (Nowak 2024), which accounts for ecosystem services of urban trees, such as the amount of carbon in biomass, its annual absorption, and precipitation retention, estimated the damage at \$54,970. According to the Ministry of Environment's tax rates, used for calculating damage to the protected natural fund with a coefficient of 10, the damage is estimated at \$2.63 million. As we can see, there is a significant discrepancy between different methodologies, especially between the State Forestry Agency and Ministry of Environment's rates—almost 60 times. Y. Didukh stresses the need for reliable evidence and the application of standardized approaches to damage assessment.

5.8. Drawbacks of methodological approaches to environmental damage assessment

The results presented above differ. According to Demidenko and Stakhiv, the reason for the discrepancies in environmental damage assessments is that the Ukrainian government uses a methodology based on calculating lost income from fees, taxes, and other regulatory payments due to pollution caused by municipal and industrial emissions (Demidenko, Stakhiv, 2023). This indicator is adjusted using coefficients that consider the impact of military destruction. According to the authors, these coefficients are difficult to justify, especially for international donors. On one hand, this allows covering a wider range of impacts, including indirect losses, but on the other hand, the approach is limited due to the subjectivity of choosing coefficients and the difficulty of international recognition of such estimates.

Demidenko and Stakhiv explain that the RDNA3 methodology, mentioned above, is based on the direct assessment of the damage to physical assets and infrastructure, considering their pre-war replacement or repair costs. This approach is more standardized and suitable for international use but does not account for indirect environmental damage, such as long-term ecosystem degradation or losses of ecosystem services.

Short Conclusions

The analysis shows the existence of several approaches to assessing environmental losses and damage caused by military actions in Ukraine. The Ukrainian government uses a methodology based on calculating lost income from fees, taxes, and other regulatory payments related to pollution from municipal and industrial emissions. International approaches, such as the World Bank or UN methodologies, focus on directly assessing damage to physical assets and infrastructure, considering their pre-war replacement or repair costs. Scientific research predominantly applies an ecosystem approach or normative assessments, particularly for agricultural lands. The results of calculations using these approaches vary significantly, which highlights the need to improve existing methodologies, create a reliable evidence base, and standardize approaches to environmental damage assessment. The analysis also shows that the number of Ukrainian scientists conducting monetary assessments of environmental damage remains limited. Foreign studies are mostly carried out by international organizations such as the World Bank and the UN. This is due to the complexity of the methodologies required to assess environmental objects and services, as well as limited access to data due to ongoing hostilities. Thus, modern methodologies should be adapted to the specific conditions of Ukraine based on the results of comprehensive studies. Accurate assessments and reliable calculations will provide the basis for justifying reparations claims and allow for predicting potential negative consequences for the environment and developing effective measures for their minimization.

Reasons for gaps in the research on monetary assessments of the military impact on Ukraine's natural environment, in our view, are as follows:

Lack of standardized methodologies:

- Insufficient development of unified methodologies for assessing environmental damage that meet international standards.
- Lack of tools for integrated assessment of direct and indirect losses.

Underestimation of indirect losses:

- The impact of military actions on agricultural ecosystems and the decrease in their productivity.
- Economic losses due to the degradation of ecosystem services.

Insufficient data:

- Lack of access to active combat zones for collecting accurate data on environmental consequences.
- Limited satellite data and lack of field observations.

Expected priorities in research on the military impact on the environment and resulting damage, in our opinion, include the following:

- Updating national damage assessment methodologies to meet international standards, including the use of UNCC (United Nations Compensation Commission) and CERCLA (based on the US Comprehensive Environmental Response, Compensation, and Liability Act) approaches.
- Integrated assessment of ecosystem losses, considering direct, indirect, and potential losses of ecosystem services.
- Development of databases for assessing the impact of military actions on the environment.
- Focus on long-term consequences
- Advocacy for international support: conducting studies that will serve as the basis for obtaining international grants and reparations.

The most active groups of researchers in Ukraine focused on studying and assessing the military impact on the environment, as well as identifying losses and damages, are affiliated with the following academic institutions:

- M.G. Kholodny Institute of Botany of the National Academy of Sciences of Ukraine, led by Academician Y.P. Didukh, is conducting research under two programs:
 - “Assessment of the impact of military actions on the transformation of terrestrial natural ecosystems using model species groups of bioindicators and monitoring of alien species in the flora and fauna as part of ensuring Ukraine's biological security”.

- “Geoinformation system for spatial assessment of environmental degradation in Ukraine due to Russian aggression”.

- National Forestry and Technical University of Ukraine (Ihor Soloviy and Lyudmyla Zahvoiska, assessing ecosystem services and damage in forest ecosystems).
- Bila Tserkva National Agrarian University (Anton Tretyak and others).
- Sumy National Agrarian University (Valentyna Tretyak, Natalia Kapinos and others). National University of Bioresources and Nature Management of Ukraine, (Liudmyla Hunko and others).

Box 5.1. Methodologies for calculating the extent of damage caused by emergencies and/or during martial law

- Order of the Ministry of Agrarian Policy and Food of Ukraine No. 295 of 18.05.2022 “On the approval of the Methodology for determining the damage and losses caused to the land fund of Ukraine due to the armed aggression of the Russian Federation”
- Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 167 of 04.04.2022 “On the approval of the Methodology for determining the extent of damage caused to land and soils due to emergencies and/or armed aggression and combat operations during the martial law period”
- Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 366 of 15.09.2022 “On the approval of the Methodology for determining the extent of compensation for damages caused to the state due to illegal use of subsoil resources”
- Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 252 of 21.07.2022 “On the approval of the Methodology for determining the damage caused by pollution and/or contamination of water, illegal use of water resources”
- Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 309 of 19.08.2022 “On the approval of the Methodology for determining the damage caused to the environment within the territorial sea, exclusive economic zone, and internal sea waters of Ukraine in the Azov and Black Seas”
- Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 175 of 13.04.2022 “On the approval of the Methodology for calculating unorganized emissions of pollutants or mixtures of such substances into the atmospheric air due to the occurrence of emergencies and/or during the period of martial law and determining the extent of damage caused”
- Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 414 of 05.10.2022 “On the approval of the Methodology for determining the damage and losses caused to the forest fund due to the armed aggression of the Russian Federation”
- Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 424 of 15.10.2022 “On the approval of the Methodology for determining the damage and losses caused to territories and objects of the natural reserve fund due to the armed aggression of the Russian Federation”.



RESCUERS CLEAR THE RUBBLE OF A BUILDING AFTER A ROCKET ATTACK. KYIV, 24 APRIL 2025.

6. Green Recovery of War-Damaged Natural and Anthropogenic Systems

Despite the fact that the Russian Federation continues to terrorize the population of Ukraine and destroy residential and industrial infrastructure with ongoing missile and drone attacks, artillery shelling, and aerial bombardment, we understand that this will not last forever. We believe that we will persevere in this struggle, and sooner or later, peace will come to Ukrainian soil. We will rebuild the devastated country, restore what has been destroyed, and construct anew, cleansing our environment from the severe consequences of war. Discussions about the principles and paths of such recovery are already actively taking place among representatives of the academic sector, policymakers, and businesspeople not only from Ukraine but also from supporting countries. Conceptually, such recovery must be as environmentally friendly as possible, using the best available technologies and practices. The term most frequently used in this context is “green recovery”.

6.1. Vision for Post-War Recovery and Development of the Country

The concept of “green recovery” and its connection to related notions such as “green economy”, “green development”, and “green growth” is analysed in the study by

Kotkovskiy et al. (2023). The authors discuss the principles of green recovery and present three models: ambitious, pragmatic, and inertial. The study also analyses the direct economic losses Ukraine has suffered as a result of hostilities and presents a regional breakdown of destroyed or damaged residential buildings as of February 2023. Special attention is paid to financial instruments that support green recovery, including green mortgage loans, loans for energy modernization of buildings, and green loans for commercial construction, among others. The authors define three stages of green reconstruction in Ukraine through 2032, with a specific action plan. The study also offers practical recommendations for green recovery in various sectors, defines the essence of the green economy, and its role in Ukraine's future post-war recovery. It argues that developing a green economy is a necessity of our time. It is noted that Ukraine currently demonstrates a basic level of preparedness in the environmental and climate domains and is only slowly implementing EU green directives, mainly due to the ongoing war.

One critical component of green economic development is the annual increase in the production and use of alternative energy sources to ensure the country's energy independence. Recent events have shown the lack of energy security associated with traditional energy and fuel sources (Bilokinna, 2023). The study provides an overview of the legal and methodological frameworks of Ukrainian and EU environmental laws, as well as national and international reports, expert assessments, monographs, and other publications that highlight the relevance of green growth on both global and national levels (Halushkina, et al., 2017). It also summarizes the principles of green post-war recovery for sustainable economic and community development. The authors justify the importance of European experience in energy transition, which relies on best available technologies and practices. They analyse changes in electricity generation and the structure of Ukraine's renewable energy market (RES). The study outlines the necessary and sufficient conditions for economic mechanisms to incentivize renewable energy generation, as well as Ukraine's forced transformation of its energy system in response to Russian aggression.

The study also explores international support programs for the development of Ukraine's energy system and demonstrates the economic feasibility of investing in renewable energy, highlighting key risks and barriers to such investments, particularly in solar energy. It argues that Ukraine's energy strategy requires ambitious reforms in the post-war recovery period to ensure energy independence and security, and to enhance the well-being of its citizens. The RES should not be viewed merely as one of the options for diversification, but as the foundation of Ukraine's energy recovery (Metelenko N. et al., 2022).

More detailed information on Ukraine's post-war recovery—considering energy and climate aspects, EU integration under the European Green Deal, and the role of local self-government in development and community resilience—is provided by Kondratiuk O. et al. (2023). A specific case study on the city of Zaporizhzhia analyses the key challenges and priority actions for green post-war recovery of the local community.

The guide presents structural-logical recovery frameworks in the form of roadmaps for the most vulnerable sectors heavily damaged during the full-scale war and critical for sustainable urban development. This guide is valuable for local governments, territorial communities, international organizations and donors, civil society organizations, and all interested in contributing to the recovery of the Zaporizhzhia region and Ukraine (Zelena knyha (Green Book), 2024).

EU integration involves preparing for the implementation of a national emissions trading system (ETS) in Ukraine, ensuring the recognition of renewable energy guarantees of origin at the EU level, establishing financial support mechanisms and investment guarantees for new generation capacities and grid restoration, improving energy labelling requirements for goods sold in Ukraine, and developing a new generation of climate strategies and documents—including a Long-Term Low-Emission Development Strategy, a Climate Adaptation Strategy, and an updated Nationally Determined Contribution (NDC).

6.2. “Green Economy” During Wartime and Directions for Its Adaptation to Resource Limitations and Management Variability

In 2024–2025, publications began to emerge regarding the adaptation of “green” economic solutions to wartime realities. In particular, Melnyk et al. (2025) propose to consider the features of ecological and economic justification of green solutions under wartime conditions. The study offers the first comprehensive analysis of the challenges and prospects for the development of renewable energy in Ukraine during the war. It examines not only the environmental and economic aspects of the transition but also the impact of martial law on energy infrastructure, investment climate, and state policy. Theoretical aspects of the transition to green energy in Ukraine reveal key ecological, economic, and social advantages of renewable energy sources compared to traditional fossil fuels. Key scenarios and strategies for post-war reconstruction of the energy sector are defined, with an emphasis on green technologies. The current state of “brown” energy in Ukraine is analysed, the potential of renewable energy sources is assessed, and the impact of war on energy infrastructure is evaluated. The authors explore the challenges and prospects of a green transition and develop recommendations for optimizing the process of post-war transition from brown to green energy in Ukraine.

The search for effective ecologically oriented solutions is linked to aligning the interests of stakeholders under conditions of extreme economic activity. In particular, Morozov et al. (2025) note that the green economy transition is impossible without active participation from all market players, including government bodies, financial institutions, and individual investors. Deeper integration of environmental and social priorities into financial processes can ensure a balance that considers the interests of society as a whole. This requires access to modern financial instruments such as green bonds, ecological funds, and public-private partnership mechanisms, which can

mobilize significant capital for environmentally oriented projects. This approach would not only help achieve sustainable development goals but also enhance the competitiveness of the national economy in the global arena.

Damaged territories and depleted community resources must be restored to meet basic needs based on green economy principles. This would enable sustainable development in the future, rather than using available material resources for short-sighted decisions. This is discussed in the work of Akymenko et al. (2025), where the authors highlight key approaches that should underlie the planning and implementation of recovery measures. This would ensure not only effective restoration of what has been destroyed but also the sustainable development of communities in line with current European standards and global trends.

Issues of restoring damaged ecosystems, especially in agro-landscapes, are examined separately. The largest losses of forested areas were recorded in Zhytomyr, Rivne, Kyiv, and Volyn regions, which together accounted for 52% of total forest loss in Ukraine due to the war. The occupation of 600,000 hectares of forest (out of approximately 10.5 million hectares of total forest area) caused direct losses to the forestry sector amounting to UAH 13.2 million. However, this figure does not account for long-term negative consequences such as ecosystem degradation, illegal logging, biodiversity loss, environmental pollution, and destruction of forestry infrastructure. Systemic problems in forest ecosystem management were identified: inadequate state policy on the use of ecosystem services, insufficient funding to address climate change consequences, outdated infrastructure, and management strategies. It is noted that ecologisation and modernization of the forestry sector in 2021 enabled a 259-fold reduction in forest fire areas through continuous remote and online monitoring. The necessity of clustering the forestry sector is justified as an innovative approach to forest ecosystem restoration. Clustering consists of uniting enterprises, scientific institutions, government agencies, banking institutions, and public organizations that cooperate and are connected by a single technological chain (Ільницька-Гикавчук 2010). This approach is aiming to balance economic, social, and environmental components of regional development.

An interesting study by Seliuchenko and Panchenko (2025) examines the dynamics of environmental protection expenditures during Russia's full-scale invasion of Ukraine. The authors identified the impact of the full-scale war on regional environmental spending policies. They calculated integral indicators characterizing the environmental spending policies of Ukraine's regions, and analysed the dynamics and specifics of environmental policy funding.

A feature of comprehensive assessments of the environment affected by war is the attempt to define the trajectory for future recovery of Ukraine's economy and territories, based on understanding the nature and specifics of actions being implemented today. The vision of "green" recovery relies on an assessment of economic prospects under conditions of energy shortages, unstable logistics, changes in labour potential, and the need to account for ongoing threats from missile and drone attacks across much of Ukraine. At the same time, Ukraine continues its path toward EU

integration. Consequently, a large number of publications focus on incorporating Euro-integration prospects into wartime and postwar economic policy. For example, the article by Voitovych and Fedyk (2024) explores strategic directions for implementing new economic goals based on industrial potential recovery, modernization of critical infrastructure, and development of innovative economic sectors. To enhance analytical support for decision-making, a systemic model of Ukraine's post-war recovery is proposed, which, according to Semenenko et al. (2025), includes an assessment of the effectiveness of regional security measures by combining economic and security management functions in war-affected territories. At the same time, scenarios are being developed (Mykytenko et al., 2025) for seven macro-regional zones of Ukraine's post-war spatial recovery: Activation Zone, Transition Zone, Eastern and Southern Decompression Lines, Western Stimulation Zone, Central Modernization Zone, and the Southeastern Industrial Belt. For the first time, hybrid reconstruction scenarios for each zone have been proposed through 2030. These synchronize social, environmental, and economic aspects, accounting for modern challenges including climate change, post-war reintegration, and infrastructure modernization.

In parallel, the legal aspects of these processes are defined by a number of Ukrainian and international scholars, including Shkurov (2025), who argues that incorporating socio-cultural, economic, and environmental factors into the legal framework substantiates the practical and managerial significance of scientific and expert research.

6.3. “Green Economy” in Ukraine’s Post-War Development

In addition to the significant impact of factors related to the full-scale Russian invasion, Ukraine must also take into account the influence of other external factors that will determine the prospects for green recovery, economic growth, and accession to the EU (Україна та Європейський Зелений курс (Ukraine and the European Green Deal, 2023, 2024). The interconnection between “green” energy and the circular economy is a foundation that contributes to the formation of a green economy. The implementation of a green economy is an important step toward sustainable societal development and environmental protection. Realizing a green economy includes measures such as the use of renewable energy sources, the implementation of energy-saving and energy-efficient technologies, and the stimulation of product manufacturing with recyclability in mind. The green economy contributes to improving quality of life, creates new jobs in the renewable technology sector, and enhances the competitiveness of the entire economy (Prokhorova et al., 2024).

If we divide the research by Ukrainian and foreign scholars into theory, methodology, and practical implementation of results in this field, we can summarize the following:

Theoretical foundations for implementing the green economy model in Ukraine are reflected in educational and scholarly works by Ukrainian and foreign scholars, such as Halushkina, et al. (2017), Kondratiuk, et al. (2023), Bilokinna (2023), Savchenko, et al.

(2023), among others. These works outline the theoretical and methodological basis of integrated strategies for green recovery under conditions of limited financial support for investment activities, as well as alignment with EU integration requirements for the general development of productive forces.

Methodological foundations of green recovery are explored in works by Chuhunov et al. (2023), Sahaidak et al. (2022), Bakry et al. (2023), Heijer et al. (2023), among others. These works justify the transition to a green recovery model, describe national characteristics of implementing the green economic policy, consider alternative financial models, detail financial tools for implementing green growth among economic actors, and propose technological and organizational solutions in the field of green construction. They also cover compliance with regulatory and technological requirements for deploying green energy in war-damaged territories, the implementation of circular economy principles in Ukraine's energy policy, renewable energy sources, green energy solutions, and mechanisms for achieving sustainable development goals during the reconstruction of war-affected areas.

Practical cases and guidelines are presented in works by Ustinova et al. (2023), Zaiets, et al. (2023), Chichkalo-Kondratska, et al. (2018), Zinchenko and Apalkov (2024), *The Green Recovery Book* (2024), among others. The authors examine emissions trading systems and guarantees of emissions policy enforcement, climate strategies, municipal budgets, key recovery benchmarks, energy security, waste recycling technologies, and circular technologies in economic processes in the context of environmental safety. The publications also analyse challenges and measures, explore green investment practices, urban green recovery, the role of civil society in green reconstruction, financing of green technologies, business capacity for green recovery, and best practices in green financing. A special focus is placed on practical examples of implementing methodological, regulatory, and management guidelines—particularly the recovery roadmap for the city of Zaporizhzhia.

Short conclusions

Green recovery of war-damaged natural and anthropogenic systems is based on integrating green policies into plans, projects, and programs, not only concerning current initiatives but also strategic documents.

Green recovery of natural-anthropogenic systems includes resource management and territorial development based on sustainable socio-economic interactions, combining European and Euro-integration requirements with the Ukrainian reality during the war and expected post-war recovery. This includes the designation of regional entities for joint post-war recovery policies:

- Sustainable and harmonious governance of green post-war economic recovery relies on a comprehensive assessment of inflicted damage, the identification of the most effective territorial development strategies, particularly in the context of

innovation potential and security needs, as well as a realistic evaluation of the labour and natural resource potential of war-affected areas in Ukraine.

- Practical examples of effective green recovery reflect a local perspective on the issue and currently lack macro-regional scale or evaluation.
- The development and substantiation of managerial decisions must consider not only Ukraine's Euro-integration prospects but also include varied forecasts/scenarios regarding the level of territorial security and its provision given current and potential resources.



TREES WITH TRACES OF HEAVY FIGHTING IN MARCH 2022. FOREST NEAR THE VILLAGE OF MOSHCHUN. KYIV REGION, 05 MAY 2024.

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