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Research Report

Ecocide as a Weapon of War: How Russian Military Aggression in Ukraine Is Creating a Long-Lasting Ecological Crisis in Eastern Europe

Alisa Chichvarina

Research Advisor: Eduardo Souza-Rodrigues

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Abstract

The main goal of this research is to analyze the environmental and socio-economic consequences of the Russian–Ukrainian war, focusing on ecocide as a general concept and its long-term implications for water, air, and soil. Using a mixed-methods approach, this study combines quantitative regression modeling and analytical assessments of publicly available governmental and NGO reports with qualitative evidence from expert interviews and case studies. Key findings highlight the transnational nature of the ecological crisis, demonstrating how localized environmental destruction negatively impacts neighboring countries. The results reveal severe disruptions to air quality, water systems, soil health, and biodiversity, and further illustrate how environmental degradation undermines economies and damages existing ecosystems. The findings suggest that air pollution, water contamination, and soil degradation combined can generate compounding and potentially disastrous long-term consequences.

1. Introduction

1.1 Background of the Russian-Ukrainian War

The Russian-Ukrainian or Russo-Ukrainian War is an ongoing armed conflict, which refers to the first invasion of Ukraine by Russia in February 2014. The war started with the Russian Federation invading the territory of the Ukrainian Donbas, consisting of the Luhansk and Donetsk regions (*see Appendix A*), resulting in the Donbas war (2014-present), after the occupation of the Autonomous Republic of Crimea, internationally recognised as part of Ukraine. During the Donbas war, Russia held multiple pro-Russian rallies and pseudo-referendums on the occupied territories of Ukraine, cyberattacked Ukrainian State structures and self-proclaimed illegal proto-state or quasi-state formations in the Donetsk and Luhansk regions of Ukraine. The conflict was widely recognised as a war by the international community after the deployment of Russian troops and missile attacks across the entire territory of Ukraine on 24 February 2022.

1.2 Ecocide as a War Crime

Based on the data from the Institute for the Study of War, Russia currently controls 19% of all Ukrainian territory, including Crimea and parts of Donbas, priorly seized to the full-scale invasion. Then–Minister of Environmental Protection and Natural Resources of Ukraine, Ruslan Strilets, said in an interview with the ‘United News’ that the environmental damage caused by Russia’s aggression against Ukraine totals 2.4 trillion hryvnias (80.01 billion CAD) and a total of 4,200 reported general cases of environmental crimes have been recorded between February 2022 and April 2024.

Since the beginning of hostilities, Russia has been violating multiple rules of the Geneva Convention and carrying out genocide of the Ukrainian nation. There have been 146,994 war

crime cases documented as of 01/11/2024, not including any war crimes against the environment. In October 2024, the former Minister of Environmental Protection and Natural Resources of Ukraine, Svitlana Hrynchuk, stated that the Prosecutor General's Office was engaged in the investigation of 209 criminal proceedings on environmental war crimes since the beginning of the full-scale invasion, 14 of which have been preliminarily classified as "ecocide".

War is not only about destruction of human-made infrastructure or human casualties but also any armed conflict causes large-scale and long-lasting environmental degradation, known as ecocide, of the affected region with possible prolonged consequences on other countries. Only 11 countries in the world currently recognize ecocide as a crime, yet no country has classified ecocide explicitly as a war crime under their criminal codes. Ukraine can potentially become the first ever country, where war crimes against the environment would be criminally penalized.

1.3 Research Objectives and Questions

This paper analyses how the war in Ukraine results in an ecological crisis not only within Ukraine but also in its neighbouring countries, focusing on three main components of the environment affected: water, air, and soil. This research topic is an overlooked area because society has been focused on other aspects and consequences of the military conflict. It is vital to understand the consequences of the conducted ecocide as it poses long-term global ecological and economic risks.

2. Literature Review

2.1 Ecocide as a Concept

The term "ecocide" has a Latin-Greek origin. It comes from a Greek οικος – 'habitat' and Latin caedo – 'to kill', which, in essence, means the destruction of the individual's habitat. However, the legal definition is relatively recent. It was developed by a panel of criminal and environmental international lawyers in 2021, defining it as "unlawful or wanton acts committed with knowledge that there is a substantial likelihood of severe and either widespread or long-term damage to the environment being caused by those acts".

Although the word "ecocide" itself was recognised by the legal community in the 21st century, the concept of crimes against the natural environment has not evolved recently, especially in warfare. Cases of ecocide as a war tactic have been known since ancient times. In the ancient world, to ensure superiority on the battlefield, warring nations resorted to various methods of environmental destruction. The Athenian king Solon, during the siege of the city of Kirra in the 6th century BC, poisoned water wells with the herb hellebore, resulting in the weakening of Kirrian army and, consequently, in the victory of Athenians in the First Sacred War. Later, in 1943, German troops flooded the Pontine Marshes with salt water to decelerate the advances of Allied Forces. This act had minimal military effect, yet devastating implications on population as

it ruined essential food supplies and fresh water access as well as encouraged the return of Anopheles flies, which would later cause a sharp rise of malaria cases. Usage of nuclear weapons in 1945 by the Americans against the Japanese cities of Hiroshima and Nagasaki, targeted bombing of factories and hydroelectric dams in Bosnia and Herzegovina during the Balkan Wars of 1992-1995 by Serbians, resulting in chemical contamination of rivers, emptying of millions of oil barrels into the sea by Iraqi troops at the end of the Gulf War in 1991 are only individual well-known documented historical examples of crimes against the environment.

Many years have passed since these events, but cases of committed crimes against the environment, categorised as "ecocide", continue to occur in the world. In retrospect, with the technological advancements in modern warfare, such actions are not only becoming more destructive but also have longer-lasting impacts on ecosystems with intensified severity.

2.2 Air Pollution in Conflict Zones

2.2.1 Overview of Air Pollution in Ukraine

Since February 2022, Russia has launched more than 9,600 missiles of various types and nearly 14,000 attack drones on Ukrainian territory. Additionally, 33,000 guided bombs were dropped. According to Ukraine's military command, 54% of all missiles launched were aimed at civilian targets, such as residential buildings, schools, power plants, factories, and other non-military infrastructure.

The former Minister of Environmental Protection and Natural Resources of Ukraine, Ruslan Strilets, commented in April 2022 that "the volume of emissions into the atmosphere during the full-scale invasion in Ukraine can already be compared to the annual emissions of a single metallurgical plant". It is important to highlight that this statement was made just 2 months into the war.

2.2.2 Sources of War-Related Air Pollution

The main sources of air pollution in Ukraine were industry (65%) and transportation (35%) before the war, based on 2020 statistics with key pollutants being NO_2 (nitrogen dioxide), SO_2 (sulfur dioxide), CO (carbon monoxide), CH_2O (formaldehyde), PM2.5 and PM10 (dust particles).

The repercussions of the war in Ukraine on air quality have been complex, dynamic and subject to significant fluctuations over time.

Major increases in air pollution have resulted from the following:

- Bombing
- Destruction of fuel storage facilities
- Attacks on industrial facilities
- Movement of military equipment
- Building destruction
- Wildfires

Decreases in air pollution indexes are an unusual phenomenon during wartime, rarely considered in traditional analysis of conflict-related impacts. However, the war-induced contraction of Ukraine's economy is reflected in the data as a negative relationship: lower GDP levels correspond to lower emissions of pollutants such as nitrogen dioxide and sulfur dioxide. This decline can be explained by the closure of factories and construction sites as well as by a reduced civilian use of vehicles, which, in turn, resulted from petrol shortages and the mass emigration of Ukrainians to other countries.

Satellite images illustrated reductions in atmospheric concentrations of NO_2 (nitrogen dioxide), fine particulate matter and CO (carbon monoxide) during the first two weeks of the war. Moreover, the airborne level of sulfur dioxide, which had increased during the first month of the full-scale invasion, decreased.

2.2.3 Effects on Air Quality

Air quality deteriorates due to military hostilities in both direct and indirect ways:

- The indirect impact includes fires in ecosystems, shelling of oil depots as well as attacks on industrial facilities and hazardous waste storage sites.
- The direct impact of hostilities includes the detonation of shells, the use of artillery weapons, and aerial bombs. Such explosions release lead, soot, sulfur, copper, iron, and carbon into the atmosphere. Entering the soil, they contaminate ground water sources, and subsequently are a threat to flora and fauna of the region.

2.2.4 Environmental and Health Repercussions

One of the most harmful compounds of a rocket is heptyl. It damages the central nervous system, mucous membranes, and respiratory organs. Significant exposure to this compound can potentially lead to loss of consciousness.

Although non-toxic emissions do not pose a direct threat to human health, they are still dangerous as they are one of the driving factors of climate change. Large-scale movement of

military equipment, including tanks, artillery, armored vehicles, and trucks, has generated large amounts of dust as well as fossil-fuel emissions. These greenhouse gas emissions further contribute to global warming. Military actions increase the risk of climate change not only in Ukraine, but also far beyond its borders.

Carbon dioxide and nitrogen oxides are being released during the explosions of ammunition depots, which are among the most active greenhouse gases that contribute to the greenhouse effect. Ammunition remains toxic even after the explosion itself. The shell casing is usually made of cast iron with impurities of sulfur and copper. Given modern technologies, it is impossible to reliably determine the composition of any weapon of foreign origin. Therefore, shell fragments, rocket fuel, as well as burnt tanks, downed aircraft and other remnants of hostilities require proper disposal, which is impossible in the active combat regions.

The combustion of petroleum products in large volumes releases carbon monoxide and carbon dioxide, benzopyrene, sulfur dioxide and sulfuric anhydride, nitrogen oxides, gaseous and solid products of incomplete combustion of fuel, vanadium compounds, sodium salts, etc. The listed compounds are extremely dangerous for the human body. In particular, the aromatic hydrocarbon benzopyrene is a powerful carcinogen and mutagen, soot is a solid combustion product, which is not only a carcinogen, but also has the ability to accumulate in the lungs and enter the bloodstream. Hence, it is vital to protect oneself from smoke in general, as well as, in particular, from fires at oil depots, ammunition depots and industrial facilities.

Acidic gases, such as carbon dioxide and sulfur dioxide, which are released during combustion, interacting with water, form acids. This can occur both in the human body, when it gets on the mucous membranes of the eyes and mouth, and when it interacts with moisture in the air, which causes acid rain.

2.2.5 Wildfires

Wildfires have occurred more frequently and spread extensively because of military operations and an inadequate number of firefighters. In 2022, there were 25 times more forest fires than in 2021. According to the estimates from the official resource of the Ministry of Environmental Protection and Natural Resources of Ukraine, as of August 2025, damage from forest fires had already amounted to 767.87 billion UAH. Such fires are dangerous not only because of pollutant emissions into the atmosphere, but also due to the destruction of ecosystems: the loss of vegetation that absorbed carbon dioxide during photosynthesis, as well as the loss of biodiversity, which negatively affects the stability of the system.

2.3 Soil Degradation During Wartime

2.3.1 Sources of Soil Degradation

The two main sources of soil degradation during wartime are the use of weapon systems and military maneuvers as well as depriving the adversary of resources. The most obvious is the direct destruction of soil and vegetation cover. Indirect effects are usually the most difficult to predict (loss of soil buffering capacity, salinization, etc.).

The detrimental consequences for soils are generally similar in all countries where armed conflicts existed: pollution with chemicals (heavy metals, petroleum products, etc.), mechanical damage to the natural structure of soils. As a most long-term noticeable secondary impacts: water and wind erosion, dust storms, flooding, surface and groundwater pollution, involvement of valuable protected lands in agriculture. Soil restoration in many countries is still ongoing (France after WWI, Vietnam after the Vietnam War, etc.). For example, in France, an exclusion area, “Zone Rouge”, remains disrupted for farming due to a heavy bombardment during WWI. Farmers in nearby regions occasionally find shells, also known as the “iron harvest”.

2.3.2 Environmental and Health Impacts

The use of military equipment leads to high levels of contamination of the territory with petroleum products, lead, and aromatic hydrocarbons. Products, which accumulate in the soil during permanent combat activities, are lead, cadmium, carbon monoxide, and petroleum products.

All types of military-technogenic loads cause severe pollution and destruction of the soil cover. The formation of a shock wave and explosion products that spread throughout the environment is characteristic for all types of ammunition. Soil deformation occurs in all directions of shock wave propagation. As a result of combustion, explosion and detonation of ammunition, various derivative products are formed, most of which are toxic or dangerous pollutants. The main source of pollution during shelling is the explosion products, which are finely dispersed particles and ions of heavy metals that infiltrate the soil with water and ammunition fragments. Initial accumulation of pollutants happens in the soil, followed by their redistribution both in the soil itself and transfer to other environments, such as surface and groundwater, vegetation, and their movement along the “soil-plant-human” trophic chain.

2.3.3 Economic Cost Assessment of Soil Damage

According to the Ministry of Environmental Protection and Natural Resources of Ukraine, the total damage to land resources amounts to 1.28 trillion UAH. This includes damage from land littering, estimated at 1.26 trillion UAH, and soil contamination, with an estimated damage of 20.96 billion UAH.

2.4 Water Contamination in War Zones

2.4.1 Main Sources of Water Pollution

One of the ecological disasters of wartime is water pollution. Despite international conventions that ban attacks on water infrastructure when civilian damage outweighs military advantage, damage to water infrastructure occurs frequently and directly or indirectly as a result of military attacks. The consequences of such attacks are deprivation of drinking water, disruption of sanitation, and pollution of surface water and groundwater.

Primary sources of water pollution during armed conflicts are the following *(see Appendix E)*:

• **Deliberate flooding**: The destruction of dams causes large areas to be flooded, washing chemicals, weapon remnants, landmines, and other pollutants from the soil.

• **Ammunition pollution**: Rocket fragments, bullets, and other explosive materials mix with river waters and other water sources, contaminating them with toxic fuels and heavy metals.

• **Discharge of untreated wastewater**: The destruction of treatment plants and sewage networks causes untreated domestic and industrial wastewater to mix with water sources.

• **Technogenic pollution**: The destruction of oil depots, industrial facilities, and other infrastructure causes the leak of petroleum products, heavy metals, and other toxic substances.

• **Mine flooding**: Mine flooding causes mine waters containing heavy metals and salts to rise, contaminating surface and groundwater sources.

2.4.2 Direct and Indirect Impacts on Water Quality

During the war in Ukraine, water resources are being polluted as a result of the destruction of infrastructure (sewer lines, treatment facilities, oil storage dams), the mining of water bodies (rivers, seas), shelling of enterprises and explosions at enterprises, which caused chemicals, fuel, heavy metals, and ammunition to enter water bodies, as well as the flooding of mines and the discharge of untreated wastewater.

All this led to deterioration in water quality, the death of aquatic organisms, threats to human health, and long-term environmental problems, such as groundwater pollution and disruption of the self-purification of water bodies. 15% of the Ukrainian population had limited or no access to safe water in April 2022.

Rivers and seas have been severely affected by the war. The destruction of infrastructure means that treatment plants, water pipes, sewage networks, pumping stations and other critical water infrastructure facilities have been significantly damaged or completely destroyed by shelling, bombing, and other combat operations, and, therefore, were unable to perform their main

function. This, in turn, led to the discharge of untreated wastewater into water bodies, leaks of hazardous substances, and interruptions in water supply.

2.4.3 Regional Consequences

The direct consequences of combat operations also include high levels of water pollution, as significant amounts of pollutants, such as petroleum products (tons of oil and diesel fuel that entered the water due to damage to oil storage facilities and oil pipelines), combat substances; heavy metals that entered the water along with other toxic substances as a result of shelling and the destruction of industrial enterprises. For example, in Mariupol, a large part of the waste and harmful substances that had accumulated over decades at the Ilyich Metallurgical Plant ended up in the Sea of Azov and later in the Black Sea. The deployment of sea- and landmines on coastal areas was a military tactic to prevent amphibious landings. Naval sonar systems for underwater vessel detection in the Black Sea have been associated with the cases of dolphin strandings. Moreover, the major ports of Odesa, Mykolayiv, and Mariupol have been repeatedly and continuously targeted by the Russian military, severely affecting Ukraine's imports and exports.

Attacks by Russian troops on dams and drainage systems caused changes in river beds, which, in turn, led to flooding in some areas and drying up in others. This disrupted natural ecosystems and damaged water resources.

Additionally, rivers can become directly polluted when military equipment crosses them. This occurs because ammunition and equipment destroyed at bridgeheads release large quantities of harmful substances into the water, including iron compounds and other chemicals.

One of the war-related water pollution ways that should be mentioned, particularly when considering the Ukrainian case, is mine flooding, which poses a risk for surface and groundwater contamination. As of July 2023, over 49 mines had been flooded in eastern Ukrainian territories occupied by Russian troops. The Oleksandr-Zakhid and Yunyi Komunar mines are considered to be the most serious threats currently. Chlorobenzene and other hazardous wastes have been stored in Oleksandr-Zakhid since 1989. Regarding the Yunyi Komunar mine, the Soviet Union detonated a 0.3-kiloton nuclear bomb there in 1979 to facilitate the release of methane.

3. Methodologies

3.1 Research Approach

This research was conducted using a mixed-methods approach, combining quantitative analysis of environmental data with qualitative insights from an interview and case studies. This approach allows a comprehensive assessment of the environmental and socio-economic consequences of the Russian-Ukrainian war, including transboundary implications.

3.2 Data Collection

3.2.1 Secondary Data

Data on damaged industrial and critical infrastructure facilities were obtained from the Ecodozor organization, which provides monthly analytical reports. Greenhouse gas (GHG) emissions data were obtained from the Initiative on GHG Accounting of War (IGGAW). Environmental data on soil and water contamination as well as air pollution were collected from the Ministry of Environmental Protection and Natural Resources of Ukraine, scientific publications, and publicly available international reports (UNEP, Nature, etc.). A case study on the destruction of the Kakhovka Dam was used to illustrate a unique perspective on how regional environmental damage can result in potential environmental crises in other countries.

3.2.2 Geographic Scope

- The analysis focuses on the most affected regions of Ukraine: Donbas, Kharkiv, Kherson, Zaporizhzhia, Mykolaiv, Kyiv, Odesa.

- Transboundary implications were considered for neighboring countries in Eastern Europe (Moldova, Romania, and Bulgaria).

3.3 Data Analysis

3.3.1 Quantitative Analysis

Monthly reports of damaged facilities were analyzed to identify local trends. Linear regression model was used to estimate future trends of cumulative CO_2 equivalent emissions. Data on water contamination, air pollution and soil degradation were analyzed using descriptive statistics to assess direct and indirect impacts.

3.3.2 Case Study Approach

Kakhovka Dam destruction was used as a case study to analyze potential environmental transboundary effects of the war.

3.4 Interviews

An interview was conducted over Zoom to complement quantitative data and gain expert insights into environmental, economic and policy implications of the war *(see Appendix F and Appendix G for more information)*.

4. Discussion / Analysis

4.1 Regional Environmental Impacts in Ukraine

It became evident from the analysis that the Russian-Ukrainian War has created a symbiotic pattern of environmental damage in each region, with different factors dominating depending on the location. The most affected Ukrainian regions by the military actions *(see Appendix B)* and, consequently, by environmental destruction are:

- Donbas (Donetsk and Luhansk): Flooding of coal mines that resulted in groundwater contamination, toxic leaks caused by destruction of metallurgical and chemical plants, soil degradation and loss of biodiversity from shelling and explosives, air pollution from detonation of industrial facilities and oil depots.
- Kharkiv: Air pollution and soil contamination from shelling of the industrial zones, water contamination from damaged infrastructure and leaked toxins in rivers, forest fires, destruction of agricultural land.
- Kherson, Zaporizhzhia, Mykolaiv: Destruction of Kakhovka Dam resulted in water pollution, salinization of soil, ecosystem transformation, etc., loss of biodiversity in the Dnipro river and Black Sea basin, agricultural devastation, radioactive risk due to continuous threats to Zaporizhzhia Nuclear Power Plant.
- Kyiv region: Air pollution due to forest fires, air and soil contamination from missiles and destroyed fuel depots, water pollution of Dnipro river, flooding due to a destruction of Kazarovychi Dam on the Irpin river, radioactive risk from shelling in the Chernobyl Exclusion Zone, including the disturbance of radioactive dust caused by the movement of heavy military equipment.
- Odesa: Marine pollution in the Black Sea due to a toxic waste from port attacks, damage of coastal ecosystems, agricultural land contamination from shelling, repercussions of underwater mines on biodiversity.

4.1.1 Infrastructure Damage Trends

According to the Ecodozor organisation, which publishes monthly analytical reports on the number of damaged industrial or/and critical infrastructure facilities, 187,594 reports of destruction or damage of these facilities were recorded in 4,180 settlements in Ukraine in the period from February 2022 to the end of July 2025. During this period, the largest number of reports of violations was recorded in the settlements of Kherson (1,786) and Avdiivka (1,523).

The high number of reported infrastructure damages in Kherson and Avdiivka can be explained by their industrial and military strategic significance. Kherson, a coastal city, has been a constant target of Russian shelling due to its access to main transport routes, ports, and agricultural regions. Avdiivka has experienced major artillery strikes for several years due to its frontline

location in the Donetsk region. The presence of the largest Ukrainian coke and chemical plants in the city also increases the likelihood of damage.

After conducting the trend analysis based on the Ecodozor data, the average monthly number of damaged facilities from July 2024 to July 2025 is approximately 52. During that time, the total number of damaged industrial and critical infrastructure facilities in Ukraine ranged from 27 to 71 per month. The highest number of incidents happened in early fall 2024 (August 2024 - September 2024), conversely, lower numbers were observed in winter months (November 2024 – February 2025). This data showed a persistent and fluctuating pattern of infrastructure damage, highlighting the ongoing environmental and socio-economic ramifications of the conflict. This trend signals the long-term potential threat of ongoing degradation to Ukraine's critical infrastructure and ecosystems.

Month	Number of damaged facilities
July 2024	60
August 2024	67
September 2024	71
October 2024	66
November 2024	42
December 2024	36
January 2025	33
February 2025	27
March 2025	52
April 2025	35
May 2025	58
June 2025	69
July 2025	64
Total	**680**

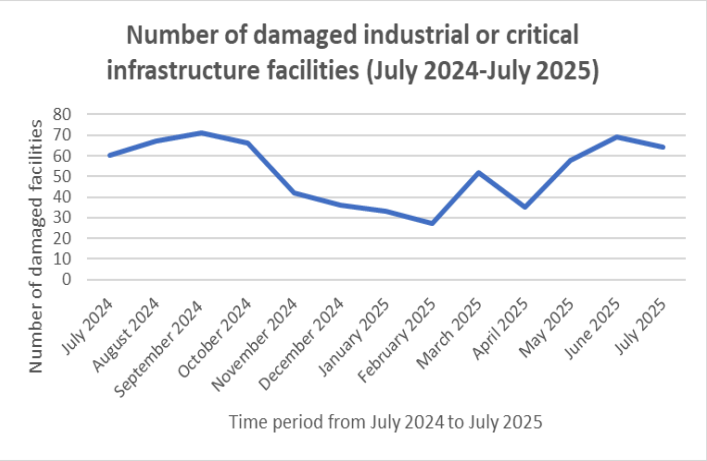


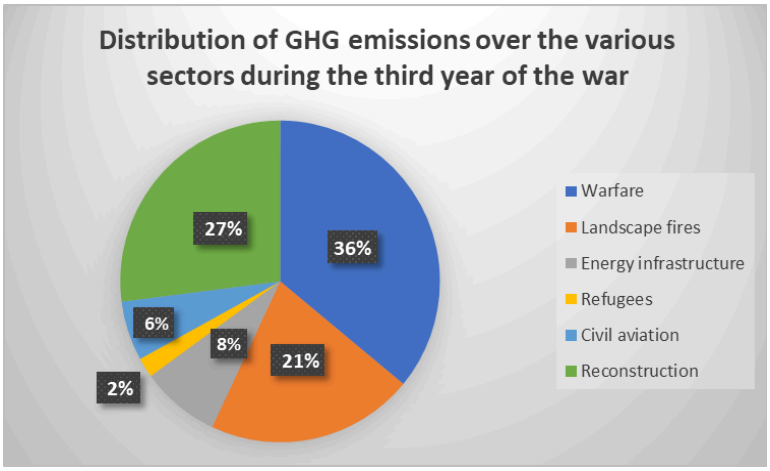
Table 1. *Number of reports on disruptions and emergency incidents at critical infrastructure facilities (July 2024 – July 2025); based on the Ecodozor data.*

Figure 1. *Monthly infrastructure disruptions in Ukraine (July 2024 – July 2025), based on data from Table 1.*

4.2 Air Pollution

4.2.1 GHG Emissions (Greenhouse Gas Emissions)

Figure 2. *Distribution of GHG emissions during 2024-2025.*



According to the Initiative on GHG Accounting of War, total emissions in Ukraine for the period of 24 February 2022 to 23 February 2025 reached approximately 230 million tonnes of

CO_2 equivalent ($MtCO_2e$). In 2024 alone, emissions spiked by 55 million tonnes CO_2e, driven largely by landscape and forest fires.

The largest contributors were:

- Warfare-related activities (tanks using fuel, ammunition production/use, fortification construction): 82.1 $MtCO_2e$ (36% of total).
- Reconstruction of damaged infrastructure: 62.2 $MtCO_2e$ (27%).
- Landscape and forest fires: 48.7 $MtCO_2e$ (21%).

During the third year of the war, emissions increased by 30% (or 55 million tons of $MtCO_2e$), compared to previous year. Emissions during the three-year period of full-scale invasion are comparable to the total annual emissions of four European countries: Austria, Hungary, the Czech Republic and Slovakia combined.

4.2.2 Linear Regression Model (Cumulative Emissions)

Based on the data provided by Initiative on GHG Accounting of War:

Timeline	**Total emissions of the CO_2 equivalent ($MtCO_2e$)**
12-month assessment (2022-2023)	120
24-month assessment (2023-2024)	175
36-month assessment (2024-2025)	229.7 (or 230 rounded)

Table 2. *Cumulative war-attributable CO_2e emissions in Ukraine (2022–2025), based on IGGAW data.*

Assumptions of the model:

I. No major escalation or de-escalation of the conflict.

Limitations:

I. Small sample (n=3) and, therefore, statistical inference is weak.
II. Data is preliminary for the period of 2024-2025, and initiative reports are often updated later.
III. Linear regression model was chosen, however, it may fail, due to drivers being non-stationary, if conditions change rapidly.

Let C_t be predicted cumulative $MtCO_2e$ after 12-month periods (t), with t=1,2,3.

(t, C):

t=1, C=120

t=2, C=175

t=3, C=230 (rounded)

As increments are equal for all given 12-month periods (55 $MtCO_2e$), a linear model is appropriate to approximate the trend (given three points lie on a straight line). Therefore, using Simple Linear Regression Line formula $y = \beta_0 + \beta_1 x + \varepsilon$:

$\widehat{C}_t = \beta_0 + \beta_1 t$, where

$\widehat{C}_t$: predicted $MtCO_2e$ after t 12-month periods

β_0 = 65 $MtCO_2e$, y-intercept (when t = 0)

β_1 = 55 $MtCO_2e$, slope, representing the increment in cumulative emissions per 12-month period

Estimated regression model: $\widehat{C}_t = 65 + 55t$

Using the estimated regression model, predicted cumulative emissions after 4 years of the war in Ukraine (t = 4) are:

$\widehat{C}_4 = 65 + 55 * 4 = 285$ $MtCO_2e$

Cumulative war-attributable CO_2e emissions in Ukraine have increased steadily from 120 $MtCO_2e$ in the period of 2022-2023 to 230 $MtCO_2e$ in 2024-2025. Using a simple linear regression model, the predicted cumulative emissions after four years of conflict (t=4) are projected to be approximately 285 $MtCO_2e$.

This trend highlights the growing detrimental environmental impact of the war, focusing on air pollution. From a policy perspective, these observations emphasize the need for continuous environmental monitoring and long-term natural-friendly solutions, such as reforestation and afforestation with fire-resistant species or funding of carbon sequestration projects, to

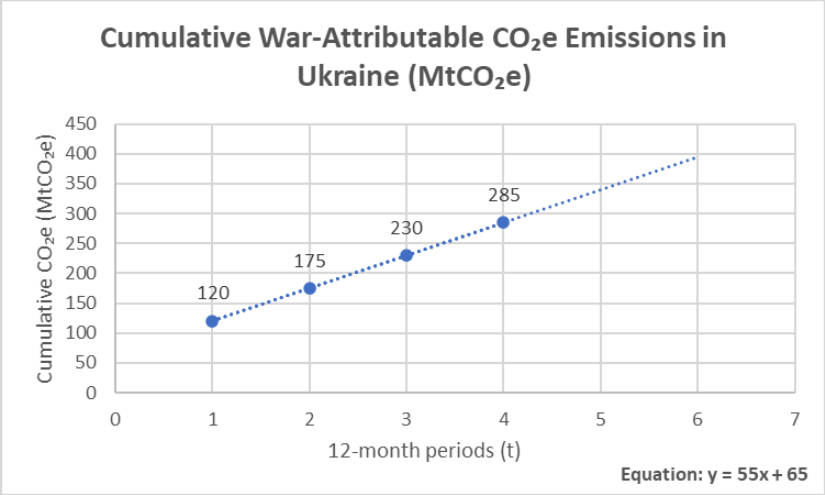


Figure 3. *Predicted cumulative war-attributable CO_2e emissions in Ukraine (2022–2025) using a linear regression model.*

mitigate and limit further ecological damage. Due to the dynamic nature of the conflict, predictions of the model carry uncertainty, which means that a de-escalation or escalation of the aforementioned conflict could potentially significantly alter emission patterns.

4.3 Soil Degradation

Soil is being impacted in both, direct and indirect ways.

4.3.1 Direct Impacts

1. Explosions and shelling: Soil compression, reduced water absorption capacity, loss of nutrients and mineral composition, loss of microorganisms' activity, soil flora and fauna degradation, reduction of bioavailability, acute toxicity (soil contamination, groundwater pollution, soil erosion and acidity).
2. Oil and fuel spills: Acute toxicity (soil contamination and groundwater pollution), soil compression, reduced water absorption capacity, loss of nutrients and mineral composition, degradation of soil flora and fauna, reduction of biodiversity.
3. Traffic of tanks and artillery: Soil degradation, land degradation by destruction of vegetation, soil compaction, and disturbance of land, which can lead to increased erosion and reduced soil fertility.
4. Landmines and unexploded ordnance (artillery shells, grenades, mortar shells, cluster munitions, improvised explosive devices, etc.): Acute toxicity (soil contamination and groundwater pollution).

4.3.2 Indirect Impacts

1. Industrial damage: Toxic leakage and chemical contamination of soil, long-term decline in soil fertility and agricultural productivity, soil erosion.
2. Agricultural damage: Land abandonment that results in loss of crops, and reduced agricultural productivity, which, in turn, affects local food supply and global food security.
3. Armed clashes (flooding as a weapon, construction of tranches and bunkers, gun fires): Biological pollution and soil erosion, with the long-term consequences on agricultural land.
4. Wildfires caused by explosions, missiles and intentional arson: Soil erosion, loss of microorganisms' activity, soil flora and fauna degradation, reduction of biodiversity, change in acid-alkanine conditions towards a neutral pH reaction.
5. Military waste: Acute toxicity (localized soil contamination and groundwater pollution).
6. Long-term bioaccumulation: Public health issue after alteration of food chains.

4.3.3 Wartime Effects on Ukrainian Agriculture, Exports and Supply Chain Disruptions

Being the 5th largest exporter of wheat and barley, Ukraine is being called a "breadbasket of Europe". In 2021-2022 (pre-war years) it accounted for 41% of sunflower oil globally, 17% of barley, 13% of corn, and 9% of wheat production and export globally. The main destinations of Ukrainian exported wheat are Egypt, Pakistan, Lebanon, Bangladesh, Indonesia. Lebanon, for example, imports 80% of its wheat from Ukraine and India imports 76% of its sunflower oil. According to the data of the UN Food and Agriculture Organization from 2020, 92% of Moldovan wheat was exported from Ukraine.

Salinization, burning, and leaking of chemicals and toxic particles have significantly decreased the area of agricultural land in Ukraine. Some of the fields are being artificially flooded, some are located in regions that are being heavily attacked and bombarded, and in some areas there is not enough labor force due to the mandatory conscription of male citizens aged 25–60. The aforementioned reasons have impacted not only the volume of Ukrainian exports but have also resulted in supply chain disruptions and food insecurity in some countries that heavily relied on Ukrainian exports.

Some effects of the food crisis were temporarily mitigated by a UN-brokered grain deal, but after the announcement of Russia on July 17, 2023 to withdraw from the agreement, they bombarded Ukraine's Black Sea ports and grain terminals, thereby restricting Ukraine's export of grain. Russia has seized most of Ukraine's coastline and blockaded it. Food can be taken out of Ukraine over land or on barges via the Danube river.

Without coordinated soil restoration efforts *(see Appendix C)*, such as manual demining, controlled detonation, chemical remediation and erosion control, soil recovery may take years. It will be necessary to establish a list of priority sites requiring immediate attention once the war ends as part of damage mitigation.

4.4 Water Contamination

4.4.1 Case Study: Kakhovka Dam Destruction

4.4.1 (a) Environmental and Economic Consequences of the Kakhovka Dam Destruction

The destruction of the Kakhovka hydroelectric power plant dam by Russian troops on June 6, 2023, caused the most devastating environmental disaster of the Russian-Ukrainian War in terms of its impact and long-term consequences. The destruction of the dam led to massive downstream flooding along the Dnipro River in the direction of Kherson, carrying organic waste, hundreds of tons of oil, landmines and unexploded ordnance into the Dnipro River Delta and the Black Sea. The collapse of the dam resulted in the release of 19.9 billion cubic meters of water from the Kakhovka Reservoir. This flooding contaminated the region's soil, submerged multiple

cemeteries and cattle burial grounds, polluted reservoirs, altered local climatic conditions, killed thousands of local plant and animal species, destroyed existing ecosystems, and created significant water supply issues. Hundreds of thousands of people lost access to safe drinking water.

Initially, a wave of water flowed downstream from the dam, flooding coastal areas. The floodwaters then washed away numerous pollutants from the soil, including chemicals stored near the shore, weapons, mines, cemeteries, and cattle burial grounds.

Upstream from the dam, the artificial reservoir disappeared, leading to local climate changes. In addition, various harmful sediments previously submerged at the reservoir bottom were exposed, further affecting the environment.

The destruction of 31 irrigation systems in Dnipropetrovsk, Kherson, and Zaporizhzhia means that 600,000 ha of arable land have lost irrigation, reducing Ukraine's harvest of grains and oil crops in 2023, valued at $1.5 billion in export volumes.

Based on estimations from the Ministry of Environmental Protection and Natural Resources of Ukraine, the approximate environmental damage from the Kakhovka dam explosion amounts to 77.8 billion UAH, with more than 100,000 hectares (247,000 acres) of agricultural land, nature parks and forests flooded downstream.

4.4.1 (b) Potential Transboundary Implications

Having analyzed multiple articles on the Kakhovka Dam destruction from *The Guardian*, BBC, and *The Washington Post*, as well as reports from international organizations (UNEP and Truth Hounds) and scientific publications (e.g., Nature), the potential impacts on Eastern European countries (Bulgaria, Moldova, and Romania) are the following:

1. **Environmental and ecological consequences**

The environmental consequences of the war in Ukraine are transnational in nature. Ukraine's water resources have suffered enormous damage as a result of Russian aggression and full-scale war, which has led to a deterioration in water quality, the destruction of water supply systems in regions where fighting continues, and long-term environmental problems both in Ukraine itself and in many countries of Eastern Europe. This has particularly affected, and will continue to have effects in the future for, those countries through which the same waterways pass as in Ukraine. These impacts extend to other countries through pollution of the Black and Azov Seas, the Dnieper, Southern Bug, and Desna rivers, posing threats to environmental security worldwide *(see Appendix D)*. The collapse of the Kakhovka Dam released polluted water from the Dnipro

River into the Black Sea, which has a coastline not only in Ukraine but also in Romania, Bulgaria, Turkey, Georgia, and Russia.

The release of heavy metals, nutrients, and pollutants into the marine environment can lead to eutrophication, harmful algal blooms, and oxygen depletion, disrupting local fisheries and marine biodiversity. Protected areas of these countries, such as the Danube Delta Biosphere Reserve, are especially at risk of experiencing such ecological disruptions.

2. **Socio-economic impacts**
    - Tourism

    Romania and Bulgaria are countries , which rely on tourism as a significant economic sector. They potentially might experience a decrease in the tourist inflow due to a water quality degradation and algal blooming in the Black Sea.
    - Agriculture and food security

    As mentioned earlier in the report, contamination of soil, water, and air with toxic pollutants due to military actions, as well as the Russian blockage of Ukrainian ports, has significantly decreased Ukrainian exports. Ukraine was a major supplier of grain, vegetables, and other agricultural products in Eastern Europe, with Moldova being one of the main trade partners. The war in Ukraine limits imports of Ukrainian agricultural products to Moldova and their re-export. Moreover, it impacts shared river systems, such as the Dniester and Danube, which might affect Moldovan irrigation and soil quality.
    - Marine fisheries

    The destruction of the Kakhovka Dam has endangered numerous species, including 43 fish species, at least six mammals, rare invertebrates and amphibians, and various waterfowl, by the influx of pollutants into the Black Sea. The water contamination can lead to reduced fish stocks due to a decrease in fish populations, impacting fisheries in Romania and Bulgaria.

Note: Data from other countries are not publicly available, therefore, the predictions presented here are based on processed information from Ukrainian sources.

4.5 Interviews

The interview was conducted on the topic of environmental and energy consequences of the Russian-Ukrainian war as well as potential strategies of post-war recovery, particularly focusing on soil, water and renewable energy resources, to complement the main research findings. Interviewee A is an expert in Ukrainian environmental and energy systems. The interview results strongly support the findings presented earlier in this report. Interviewee A highlighted soil degradation, water contamination, and biodiversity loss as the most long-lasting environmental concerns.

Military activities, including weapon residues, fires, and accidents, are primary sources of contamination affecting air, water, and soil quality. The discussion of the Kakhovka Dam destruction reinforced the report's assessment of the environmental and socio-economic consequences, including disruptions to agriculture, energy production, and local ecosystems. Furthermore, the interviewee emphasized the need for decentralized and renewable energy solutions, particularly solar, wind, and bioenergy, aligning with the report's analysis of potential pathways for sustainable post-war reconstruction. The challenges identified, such as long-term contamination, insufficient technological capacity, and the risk of corruption, also reinforce the report's conclusions regarding the complexity of ecological and economic recovery in Ukraine. The long-term consequences of ecocide will require innovative, decentralized, and locally tailored solutions.

5. Limitations

Some challenges I faced were the unavailability of certain data from public sources I initially planned to analyze. This is due to the fact that some of this information may be classified by government agencies for safety reasons during wartime. Therefore, the analysis relies only on publicly available data, which may be delayed and may not be fully applicable at the time of the analysis. Hence, the report is not as comprehensive due to the dynamic environment of the conflict in Ukraine.

To minimize research errors in the selected measurements and subindicators, the collected data covers the period from February 24, 2022 to August 30, 2025, to ensure its relevancy. As a result of time constraints and limited level of access, fewer sources were analyzed than originally anticipated.

In addition, another significant limitation I would like to highlight is the lack of reliable data from currently occupied territories by the Russian army. In these regions access is restricted, independent specialists are denied entry, and official reporting is either unavailable or inconsistent. No relevant data could be found on environmental destruction in Crimea and some areas of Donbas, as there is only subjective and insufficient information from pro-Russian media sources since these territories have been occupied by Russia since 2014.

6. Conclusion

The environmental impacts of armed conflicts extend far beyond combat zones, affecting neighboring regions and contributing to broader global ecological ramifications. In the case of Ukraine, the Russian-Ukrainian War caused severe and long-lasting damage to water sources, soil, biodiversity and agricultural productivity, with transboundary implications for Eastern Europe.

The destruction of key infrastructure, such as the Kakhovka Hydroelectric Power Plant and other dams, in addition to the contamination of waters with heavy metals, nitrogenous compounds, and

explosive residues, has led to significant ecological degradation. These actions have disrupted local ecosystems and caused the death of regional flora and fauna. Water pollution and soil deterioration pose immediate and long-term threats to human health, including increased risks of various diseases.

The combination of international coordination, scientific and financial resources, as well as extensive funding will be vital for Ukraine's environmental systems' restoration.

Addressing these challenges is essential not only for Ukraine but also for the broader Eastern European region. The ongoing contamination and destruction of environmental resources exemplify the concept of ecocide, emphasizing the urgent need for global support, accountability, and sustainable recovery strategies. Ensuring access to rehabilitating ecosystems and implementing resilient infrastructure must be central to post-conflict reconstruction and long-term environmental protection.

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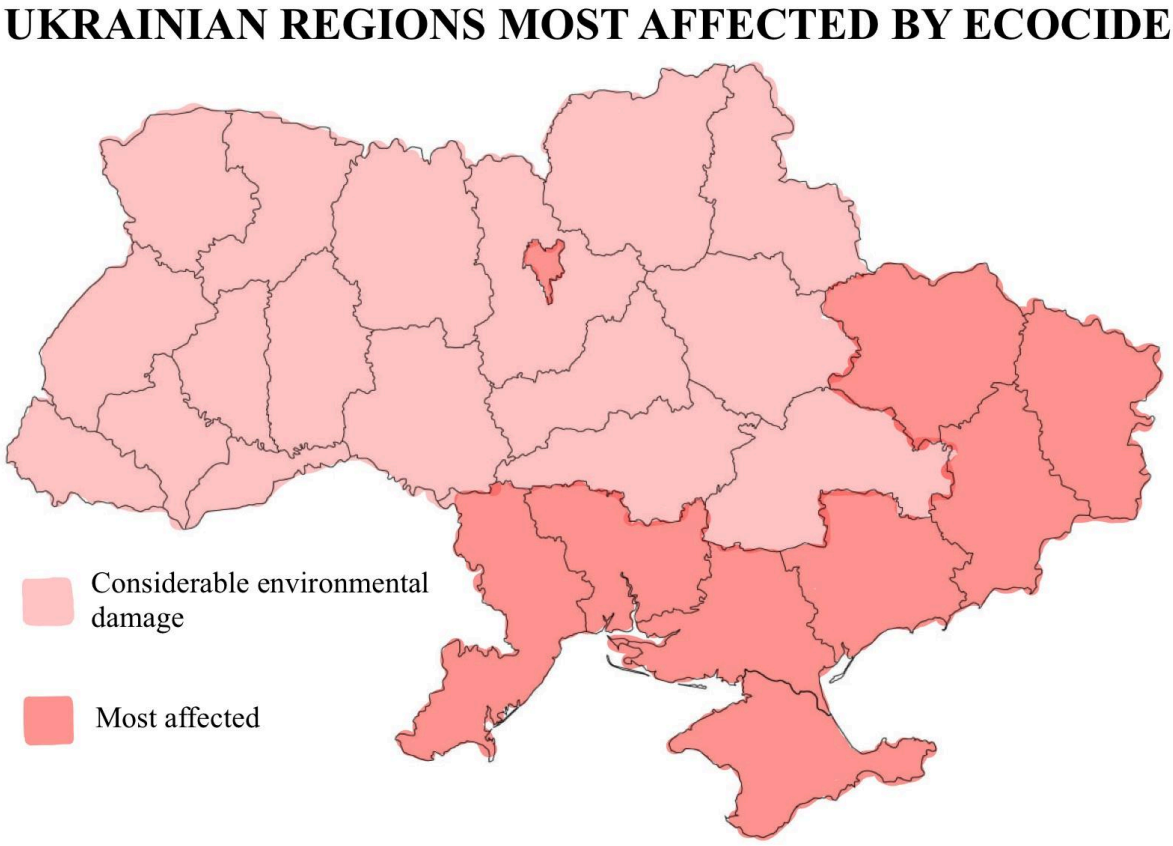
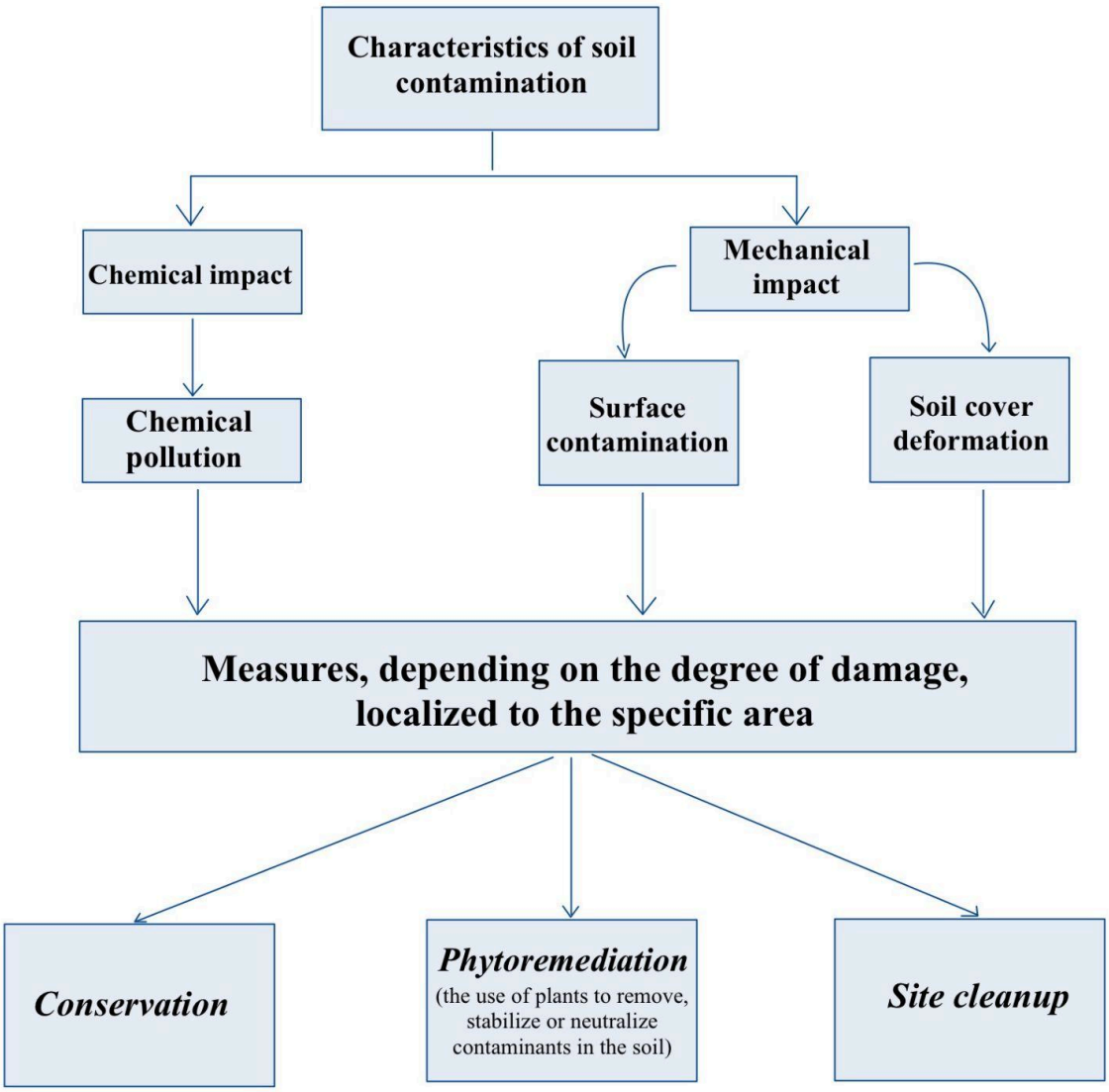
Appendices

Appendix A - Map of the Donbas Region

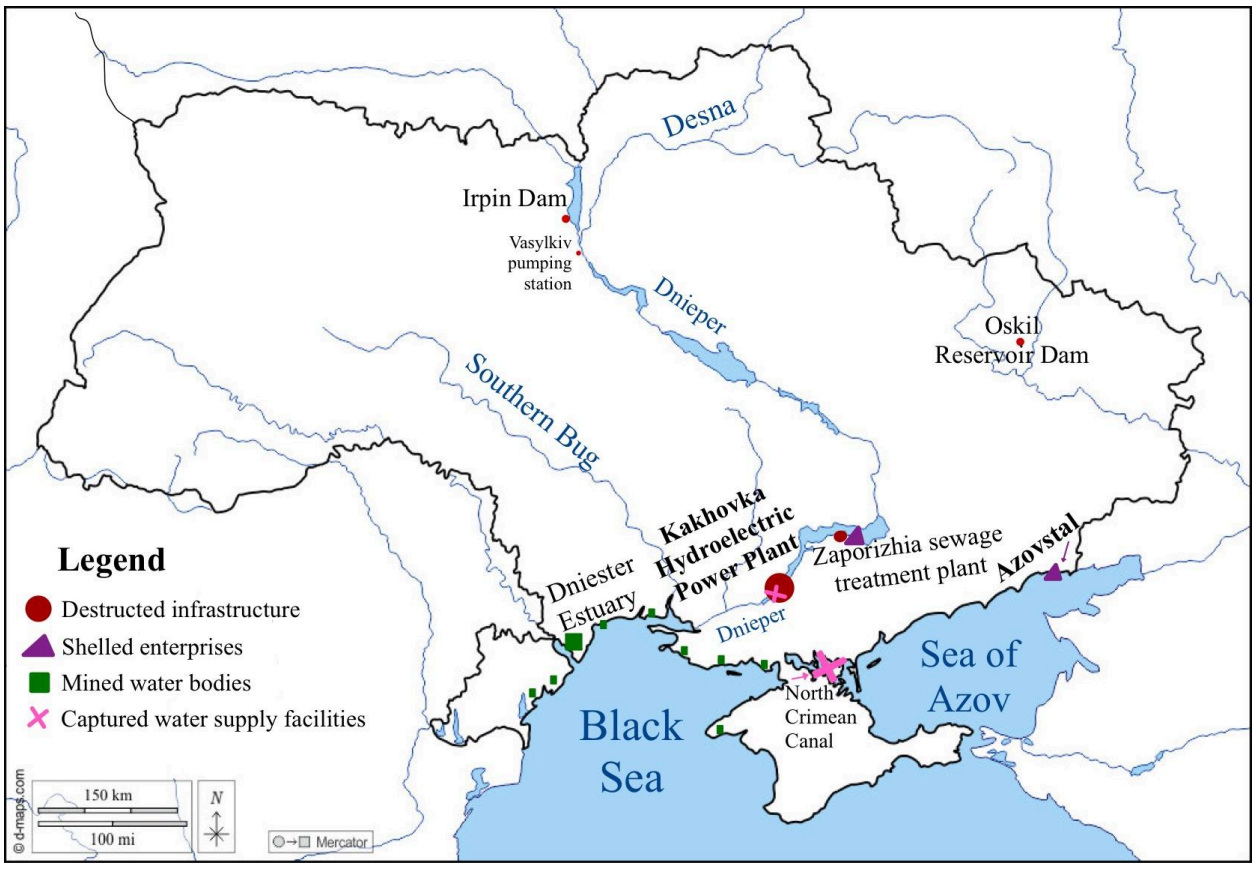
Appendix B - Map of Ukrainian Regions Most Affected by Ecocide



Appendix C - Soil Contamination: Characteristics and Remediation Measures



Appendix D - Map of Ukrainian Water Resources and Selected Infrastructure Affected by Ecocide



Source: adapted from d-maps.com, https://d-maps.com/carte.php?num_car=2658&lang=en

Appendix E - Military Actions and Their Impacts on Water Resources

Military action	Affected infrastructure/water bodies	Consequences	Examples
Destruction of infrastructure	Dams (oil storage dams), reservoirs, sewage systems, treatment facilities, pumping station	Release of pollutants, disruption of water supply, flooding	Destruction of Irpin Dam (Kyiv region), Oskil Reservoir Dam (Kharkiv region), Kakhovka Hydroelectric Power Plant (Kherson region), Vasylkiv pumping station (Kyiv region), Zaporizhia sewage treatment plant (Zaporizhia region)
Mining of water bodies	Rivers, estuaries, seas (Dnipro, Southern Bug, Black Sea, Azov Sea)	Pollution with chemicals, fuel, heavy metals, ammunition; navigation hazards	Destruction of the Dniester Estuary, mining of the Black Sea coastline
Capture of water supply facilities	Reservoirs, canals, water intake systems	Water shortages, restricted access, politicization of water resources	North Crimean Canal, Kakhovka Reservoir
Shelling/Explosions at enterprises	Oil depots, metallurgical plants, nuclear facilities, industrial sites	Spillage of oil and chemicals, fires, radioactive risks, long-term contamination	Damage of Azovstal (Mariupol), shelling at Zaporizhzhya Nuclear Power Plant, burning/shelling of oil depots across Ukraine

Appendix F - Consent Form

Ecocide as a Weapon of War: How Russian Military Aggression in Ukraine Is Creating a Long-Lasting Ecological Crisis in Eastern Europe

Interview Information Sheet and Consent Form

To decide whether you want to be a part of this research study, you should understand what is involved and what the potential risks and benefits might be. This form gives you detailed information about the research study, which will be discussed with you. If you would like to receive more information about the project, you may contact the Principal Investigator, Alisa Chichvarina, at [***mail.utoronto.ca].

The research study is being supervised by Eduardo Souza-Rodrigues who is an Associate Professor at the Department of Economics at the University of Toronto. You may contact the Supervisor, Eduardo Souza-Rodrigues, at [***@utoronto.ca].

Purpose of this research

The purpose of this research is to analyze the ecological and economic consequences of the ongoing Russian-Ukrainian war, focusing on ecocide as a weapon of war and its global implications for Ukraine and its neighboring Eastern European countries. This includes examining environmental damage such as water contamination, soil degradation, and air pollution, which results in lasting economic and geopolitical repercussions. The research will be conducted using a mixed-methods approach, incorporating both qualitative data from interviews with industry professionals and quantitative analysis from environmental and economic data.

Participant Responsibilities

You will be asked to participate in an interview to discuss these issues either **in person, virtually via Zoom, or by responding to interview questions via a Google Form.** The interview will last approximately one hour, depending on your availability and interest. **If you choose to respond via the Google Form, your responses will be recorded in writing.** You will be invited to share your professional insights, expertise, and experiences related to the environmental or economic impacts of the war in Ukraine. You are free to decline to answer any question and may withdraw from the interview at any time without penalty.

Possible Risks

There are no physical risks associated with this study. There may be minimal psychological or emotional risks. Some participants may feel discomfort discussing war-related topics. Participants are not obligated to answer any questions that make them uncomfortable and may withdraw from the interview at any time without consequence.

Possible Benefits

There are no direct personal benefits from participating in this study. However, your input will contribute to a deeper understanding of how war affects environmental, political, and economic systems. The findings may help inform academic research and enhance global awareness of ecocide and its consequences.

Confidentiality & Privacy

No information about your identity will be shared with anyone or published without your permission, unless required by law. **The University of Toronto research ethics program representatives may have confidential access to the data for monitoring purposes to ensure participant protection procedures are followed.**

The interview will be recorded **(only if consented)** and then transcribed **word-for-word**. **All personal details, such as your phone number, email address, home/work address, will be removed from the transcript and replaced by a unique study ID number. A separate file linking your name to this study ID will be stored in an encrypted, password-protected zip file and kept separately from your interview data. This file will remain encrypted at all times and will only be decrypted during active analysis. It will be permanently deleted once data analysis is complete and before the results are published, unless you have explicitly agreed to be identified.**

Audio/video recordings will be stored securely on a password-protected laptop, accessible only to the Principal Investigator. Unless you give explicit permission, your name and identity will not appear in any publications. If quotes are used, they will be anonymized unless you explicitly permit the use of your legal name. All data will be retained for as long as required (typically 7 years) following the completion of the research, and then destroyed according to University of Toronto regulations.

Participant Withdrawal

Your participation in the study is voluntary, and you may withdraw at any time. If you decide to withdraw before or during the interview, your data will be destroyed and will not be used in the study. If you withdraw after the interview but before data analysis is finalized and the research findings are published, you may contact the Principal Investigator to request that your data be destroyed.

Participant Compensation/Costs

You will not receive any compensation for participating in the study, and there are no associated costs to participate.

Sponsorship

This study is funded by the Laidlaw Foundation through the Laidlaw Leadership & Research Programme.

Conflict of Interest

The Principal Investigator, Alisa Chichvarina, declares no conflict of interest.

Contact Information

If you have any questions about the research, please contact the Principal Investigator of the study:

Alisa Chichvarina
University of Toronto
[***@mail.utoronto.ca]

If you have any questions about your rights as a subject in a study or injuries during a study, please contact Daniel Gyewu, Health Sciences Research Ethics Manager, Research Oversight & Compliance Office, University of Toronto at telephone (416) 978-3165 or by email: d.gyewu@utoronto.ca.

Consent Statement

If you would like to participate in this research study, please select either YES or NO for each of the following statements:

	YES	**NO**
1. I consent to participate in the interview by responding to interview-related questions via a Google Form, as determined by the Principal Investigator (no recording).		
2. I consent to participate in an in-person interview (audio recording).		
3. I consent to participate in a recorded Zoom interview (audio recording, and if consented – video recording).		
4. I agree to be re-contacted for clarification purposes.		
5. I agree to be quoted directly.		
6. I agree to be quoted directly if my name is not published and a made-up name (pseudonym) is used.		
7. I consent to the researcher using quotations from me and information I provided during the interview in any published materials.		

I have read and understood the provided information and have had an opportunity to ask questions. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason and without cost. I understand that I will be given a copy of this consent form. I voluntarily agree to take part in this study, following the terms specified above.

Name of Participant

Participant's Signature Date

Appendix G - Interview Questions

[Ukrainian version (original)]

- На Вашу думку, які екологічні наслідки російсько-української війни матимуть найбільш тривалий вплив на економіку та інфраструктуру України?
- Чи є, на Ваш погляд, екологічні наслідки війни, які залишаються недостатньо дослідженими або недооціненими, особливо з точки зору економічного впливу?
- Які основні джерела забруднення водних та енергетичних ресурсів, пов'язані з воєнними діями, Ви виділили б як найбільш критичні?
- Як руйнування Каховської гідроелектростанції позначилося на відновлюваних джерелах енергії та екосистемах регіону?
- А які зараз найголовніші ресурси, саме Renewable Energy в Україні використовується під час війни?
- Які довгострокові наслідки порушення аграрного та енергетичного виробництва України для регіональної продовольчої та енергетичної безпеки Ви прогнозуєте?
- Які політичні та економічні ініціативи наразі реалізуються з метою відновлення зруйнованих територій та розвитку стійкої інфраструктури?
- Які механізми екологічного та енергетичного відновлення Ви вважаєте найбільш реалістичними для територій, постраждалих від війни?
- З Вашого досвіду, які методи найбільш ефективні для оцінки фінансових втрат від екологічних та енергетичних збитків, спричинених війною?
- Які виклики виникають під час оцінки економічної вартості відновлення енергетичної та екологічної інфраструктури?
- Чи можете Ви навести приклади успішного впровадження відновлюваних джерел енергії або екологічного відновлення після конфліктів, які могли б бути релевантними для України?
- Наскільки серйозною є загроза пошкодження атомних електростанцій (наприклад, Запорізької та Чорнобильської) для енергетичної безпеки України та сусідніх країн?
- Які політичні та економічні бар'єри перешкоджають визнанню екоциду та включенню відновлюваної енергетики до стратегії відновлення після війни?
- Якщо б Ви могли змінити одну політику щодо відновлення економіки та екології в Україні, що б це було і чому?

[English version]

- What environmental damages have had the most significant long-term effects from the Russian-Ukrainian war so far?
- What do you think are the most overlooked ecological consequences of the war?
- What are the main sources of water pollution resulting from the war?
- How has the destruction of the Kakhovka Dam impacted local ecosystems?
- How has Ukraine's level of agricultural productivity been impacted by soil degradation?
- What are the long-term consequences of Ukraine's agricultural disruption on food security in Eastern Europe?
- What policy initiatives, if any, are currently being implemented to restore war-damaged farmland and recover agricultural productivity?
- What kind of environmental amendment is practically achievable for war-contaminated agricultural areas?
- Based on your experience, which techniques are the most accurate for calculating the financial impact of ecological damage?
- What challenges arise when attempting to measure the financial cost of environmental damage?
- Can you share any examples of successful ecological damage valuation or restoration following a conflict?
- How credible is the threat of an attack on nuclear power plants like Zaporizhzhia and Chernobyl and what are the potential implications in case it is highly possible?
- What are the current political barriers to classifying ecocide as an international war crime?
- Do you believe that international organizations are doing enough to address the environmental consequences of war?
- Which one policy regarding ecocide in the war-torn zones would you change if you could?

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