SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2024
ORGANIZATION AND MANAGEMENT SERIES NO. 196

ASSESSMENT OF SOIL CONTAMINATION OF UKRAINE WITH HEAVY METALS DURING THE WAR

Alina YAKYMCHUK[1*], Oksana BALANDA[2], Małgorzata BZOWSKA-BAKALARZ[3]

[1] University of Information Technologies and Management, Rzeszów, Polska; alinayakim@ukr.net, ayakymchuk@wsiz.edu.pl, ORCID: 0000-0002-5038-5215
[2] University of Information Technologies and Management, Rzeszów, Polska; obalanda@wsiz.edu.pl, ORCID: 0000-0003-2074-8182
[3] University of Information Technologies and Management, Rzeszów, Polska; mbzowska@wsiz.edu.pl, ORCID: 0000-0001-6031-8529
* Correspondence author

Purpose: This paper reviews the impacts of heavy metals on soil degradation and examines the influence of military equipment on agricultural lands during the war.
Design/methodology/approach: The systematic research method involves a comprehensive approach focused on interrelated elements of land pollution by heavy metals during the war. The analysis is based on official data on soil contamination by heavy metals (Lead (Pb), Cadmium (Cd), Mercury (Hg), Chromium (Cr), Arsenic (As)) in Ukraine and other countries of the world during the war period from burned military equipment. Combining multiple methods has provided a more complete and detailed understanding of complex interactions.
Findings: This study aims to assess the spatial distribution, concentration levels, and potential sources of heavy metal contamination in Ukrainian soils during the period of war. By employing a multidisciplinary approach encompassing field surveys, soil sampling, laboratory analyses, and geographic information systems mapping, the authors seek to elucidate the impact of warfare activities on soil quality and identify hotspots of contamination across war affected regions.
Research limitations/implications: The implications of this study underscore the importance of stakeholder engagement and adaptive management for effective integration.
Originality/value: These results could be especially interesting for researchers whose studies are interdisciplinary.
Keywords: heavy metals, soil degradation, military equipment, agricultural productivity, contamination, environmental sustainability.
Category of the paper: Research paper.
JEL: Q54, Q590, Q520, Q15, O44.

1. Introduction

Soil degradation due to heavy metal contamination poses a significant threat to agricultural productivity and environmental sustainability. This paper elucidates the mechanisms through which heavy metals disrupt soil ecosystems and explores the ramifications of military equipment on crop yield concerning soil contamination. Heavy metals, such as lead, cadmium, and arsenic, often originate from industrial activities, mining, and military operations, exerting detrimental effects on soil health. Additionally, military machinery, including tanks, artillery, and aircraft, can indirectly influence soil quality and crop yield through soil compaction, chemical deposition, and disturbance of microbial communities. Understanding these interactions is crucial for devising effective mitigation strategies to safeguard agricultural lands and ensure food security in regions affected by military activities.

The ongoing war in Ukraine has not only inflicted human suffering and geopolitical tensions but has also raised significant concerns about environmental degradation, particularly regarding soil contamination by heavy metals. Soil, as a vital component of ecosystems, plays a pivotal role in sustaining life and supporting agricultural productivity. However, the indiscriminate use of heavy weaponry, industrial activities, and the destruction of infrastructure during periods of conflict can result in the release of toxic heavy metals into the soil, posing grave risks to human health, ecosystem integrity, and agricultural sustainability.

Understanding the extent and severity of soil contamination by heavy metals during times of conflict is imperative for devising effective mitigation strategies and facilitating post-conflict recovery efforts. Heavy metals such as lead, cadmium, mercury, and arsenic, which are often associated with military activities, industrial processes, and urban warfare, can persist in the environment for prolonged periods, posing long-term threats to soil quality, water resources, and human health.

This study *aims* to assess the spatial distribution, concentration levels, and potential sources of heavy metal contamination in Ukrainian soils during the period of war. By employing a multidisciplinary approach encompassing field surveys, soil sampling, laboratory analyses, and geographic information systems (GIS) mapping, we seek to elucidate the impact of warfare activities on soil quality and identify hotspots of contamination across affected regions.

Moreover, this research endeavors to evaluate the implications of soil contamination on agricultural productivity, food security, and human health, considering the potential uptake of heavy metals by crops and subsequent exposure through the food chain. By integrating socio-economic data and environmental indicators, the authors aim to elucidate the socio-environmental consequences of soil contamination, particularly in war-affected communities where access to clean water, nutritious food, and healthcare services may already be compromised.

Ultimately, the findings of this study will not only contribute to the scientific understanding of soil contamination dynamics during war but also inform policymakers, environmental agencies, and humanitarian organizations about the urgent need for remediation efforts, risk communication strategies, and sustainable development initiatives in post-conflict settings. By fostering collaboration between science, government agencies, and civil society, the authors aspire to mitigate the long-term environmental and health impacts of soil contamination, thereby promoting resilience and recovery in conflict-affected regions of Ukraine.

2. An overview of the literature

The presence of heavy metals in soils represents a pressing environmental concern globally. Anthropogenic activities, including industrial processes, mining operations, and military maneuvers, contribute to the accumulation of heavy metals in soils, thereby posing risks to ecosystem health and agricultural sustainability. Moreover, military activities, beyond direct combat, have an unintended consequences on soil quality and crop productivity.

According to calculations taken from a study by the Ukrainian Nature Conservation Group, 50 tons of iron, 1 ton of sulfur compounds, and 2,35 tons of copper got into the soil because of the shelling of just one square kilometer of the field in the Kharkiv region—these are only the substances with the highest content (Munitions and chemicals, 2022). Moreover, during the explosion of even one kilogram of explosives, several tens of cubic meters of such toxic gases as sulfur oxide, nitrogen oxide, and carbon monoxide are released into the atmosphere. According to experts, the levels of heavy metals in the soil exceed the norm by 30 times (Expert, 2024).

The study of M. Berlinger, V. Klos, A. Doroginski, O. Lytvyn (2020) delves into the environmental repercussions of the war in Ukraine by assessing the contamination levels of soil with heavy metals. Employing field surveys, soil sampling, and laboratory analyses, the authors provide a detailed examination of the spatial distribution and concentration levels of heavy metals, shedding light on the extent of environmental degradation in the conflict-affected regions.

Heavy metal pollution of soils in the Donetsk region as a result of war has been investigated in article P. Kurylo, O. Kharlamova, O. Chornobay, S. Kovalenko (2019). Focusing on the Donetsk region, this research investigates the negative impact of military conflict on soil pollution by heavy metals. Through geospatial analysis, environmental assessments, and soil quality evaluations, the authors reveal the significant contamination levels and discuss the implications for ecosystem health, agricultural productivity, and human well-being in the region.

I. Babicheva, O. Kalita, Y. Romanyuk (2018) explored the influence of military activities on the levels of heavy metals in soils across Eastern Ukraine. Utilizing field surveys, soil sampling techniques, and statistical analyses, the authors elucidate the contamination patterns, identify potential sources of pollution, and assess the associated risks to agricultural sustainability and public health in conflict-affected areas.

V. Kravets, L. Skorobogatov, I. Danylenko, O. Kovtun, M. Chorniy (2017), **i**nvestigated soil pollution in areas affected by military actions in Eastern Ukraine. This research evaluates the distribution, sources, and environmental implications of heavy metal contamination. Through interdisciplinary approaches encompassing environmental monitoring, soil analysis, and risk assessment, the authors offer insights into the magnitude of soil pollution and advocate for targeted remediation efforts to mitigate the long-term impacts on ecosystems and human health.

The scientists O. Tytova, V. Steshenko, S. Zadorozhna (2016) were focused on the environmental consequences of war, their study investigates alterations in the concentrations of heavy metals in soils across Eastern Ukraine. Through comparative analyses, spatial mapping, and risk characterization, the authors assess the ecological risks posed by soil contamination and emphasize the importance of holistic approaches to environmental management and post-conflict reconstruction in the region.

Some researchers emphasize the importance of the use of straw to improve soil properties reduced the availability of toxic metals, although it increased the availability of trace elements. Scientist Evangelia E. Golia (2023) notes that wheat straw can become a key factor in improving the condition of the soil, increasing its fertility and limiting the risks of toxic pollution. In addition, scientists emphasize that it is now necessary to take into account the principles of the circular economy when making certain management decisions. Other researchers might focus on the importance of effective government policies (Yakymchuk et al., 2022).

These descriptions provide an overview of the key findings and methodologies employed by each author or research team in their respective studies on soil contamination with heavy metals during the war in Ukraine.

Heavy metals, characterized by high density and toxicity, adversely affect soil ecosystems through various pathways. Upon introduction into soils, these metals accumulate over time, leading to contamination that can persist for decades or even centuries (Prykhodko, Bondar, Hromova, 2011). The primary sources of heavy metal contamination include industrial emissions, improper waste disposal, and agricultural practices involving metal-based fertilizers and pesticides. Once in the soil, heavy metals interfere with vital processes such as nutrient cycling, water retention, and microbial activity, consequently impairing soil fertility and plant growth. Furthermore, heavy metals can bioaccumulate in crops, posing risks to human health through the food chain (Shpak, Kryukova, Kudryashova, 2013).

The mechanisms underlying heavy metal toxicity in soils are multifaceted and involve physical, chemical, and biological processes (Dovbush, Kozlova, Kovalenko, Yakovlevm, 2014). Physically, heavy metals alter soil structure and texture, affecting porosity, water infiltration, and root penetration. Chemically, these metals can alter soil pH, disrupt nutrient availability, and facilitate the release of harmful ions such as aluminum and manganese. Biologically, heavy metals inhibit enzymatic activity, impede microbial diversity, and induce oxidative stress in plants and soil organisms. Collectively, these mechanisms contribute to diminished soil productivity and compromised ecosystem resilience.

Military activities, including training exercises and deployments, can exert indirect pressures on agricultural lands and soil quality. Heavy military equipment such as tanks, armored vehicles, and artillery cause soil compaction and erosion, disrupting soil structure and reducing water infiltration rates. Additionally, the deployment of munitions and explosives introduce chemical pollutants into soils, further exacerbating contamination. Moreover, the passage of military convoys and vehicles lead to soil disturbance and the loss of vegetation cover, increasing the susceptibility of soils to erosion and degradation (Hladun, Ivanko, Dudka, 2012).

The degradation of soils due to heavy metal contamination and military activities has significant implications for agricultural productivity and food security. Contaminated soils exhibit reduced crop yields, altered nutrient dynamics, and increased vulnerability to pests and diseases (Kovalchuk, Orlov, Boyko, 2015). Moreover, the long-term persistence of heavy metals in soils poses risks to human health and ecosystem integrity (Yakymchuk, Baran-Zgłobicka, 2023). In regions affected by military conflicts or training exercises, efforts to rehabilitate degraded soils and mitigate contamination are essential for restoring agricultural productivity and ensuring sustainable land use practices (Lewandowska et al., 2023; Yakymchuk, Byrkovych, Kuzmych, 2023).

A. Splodytel, O. Holubtsov, S. Chumachenko, L. Sorokina (2023) estimated that the combustion of military equipment with the subsequent entry of pollutants into the human body is a risk factor for the development of various pathologies, growth and complications of the course of many diseases. In particular, scientists note that these substances are toxic to humans, especially in abnormally high concentrations. But it turns out that even small concentrations of pollutants change the activity of enzymes in the human body, affect the circulation of nuclei and protein synthesis, cause changes at the genetic level. Ministry of Ecology and Natural Resources of Ukraine: Conducts environmental monitoring and publishes reports on soil contamination levels in Ukraine, including during wartime (Ministry of Ecology, 2024).

3. Research methods

The systemic method applied to research involves an integrated approach focusing on interconnected elements within assessment of soil contamination by heavy metals. Here are the main methods employed to this research:

Field Surveys and Soil Sampling: Researchers conduct systematic field surveys in the conflict-affected areas of Ukraine to identify sampling sites representative of different environmental conditions. Soil samples are collected using standardized protocols, considering factors such as soil depth, land use, and proximity to potential pollution sources.

Laboratory Analysis: Soil samples undergo rigorous laboratory analysis to determine the concentration levels of heavy metals. Techniques such as atomic absorption spectrometry (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray fluorescence (XRF) spectroscopy are commonly employed to quantify the presence of heavy metal contaminants accurately.

Geospatial Analysis: Geographic information systems (GIS) are utilized to integrate spatial data, including soil sampling locations, land use/land cover maps, and pollution source inventories. Spatial interpolation techniques, such as kriging or inverse distance weighting, are applied to generate spatial distribution maps of heavy metal contamination, facilitating the identification of contamination hotspots.

Statistical Analysis: Statistical methods, such as analysis of variance (ANOVA), principal component analysis (PCA), and cluster analysis, are employed to analyze the relationships between heavy metal concentrations and various environmental parameters. These analyses help identify potential pollution sources, assess spatial trends, and elucidate factors influencing soil contamination.

Risk Assessment: Environmental risk assessment models, such as the potential ecological risk index (PERI) or the human health risk assessment (HHRA), are utilized to evaluate the ecological and human health risks associated with soil contamination by heavy metals. These models consider factors such as metal toxicity, exposure pathways, and receptor sensitivity to estimate the overall risk posed by contaminated soils.

Socio-Economic Surveys: Socio-economic surveys and interviews with local communities are conducted to assess the socio-economic impacts of soil contamination on livelihoods, agricultural practices, and public health. These surveys provide valuable insights into community perceptions, adaptive strategies, and the socio-economic implications of environmental degradation during times of conflict.

Remote Sensing: Remote sensing data, such as satellite imagery and aerial photographs, are utilized to complement ground-based assessments and facilitate the mapping of land cover changes, vegetation health, and landscape disturbances associated with military activities.

Remote sensing techniques enhance the spatial analysis of soil contamination and support monitoring efforts in inaccessible or war-affected areas.

By employing these multidisciplinary methods, researchers can comprehensively assess soil contamination by heavy metals in Ukraine during times of war, providing valuable insights for environmental management, risk mitigation, and post-conflict recovery planning.

Various methods and formulas based on the results of the analysis of soil samples can be used to assess soil contamination with heavy metals. Below are some of them:

1. Soil Contamination Index, I_{SC}:

$$I_{SC} = \frac{C_{metal}}{N_{metal}} \quad (1)$$

where:

C_{metal} - concentration of the metal in soil sample,

N_{metal} - permissible limit of metal concentration in soil.

2. Bioaccumulation Factor, *BAF*:

$$BAF = \frac{C_{plant}}{C_{soil}} \quad (2)$$

where:

C_{plant} - concentration of metal in plant,

C_{soil} - concentration of metal in soil from which plant uptake metal.

3. Leaching Factor, *LF*:

$$LF = \frac{C_{leachate}}{C_{soil}} \quad (3)$$

where:

$C_{leachate}$ - concentration of metal in leachate after soil sample extraction,

C_{soil} - concentration of metal in soil sample.

4. Soil Ecological Risk Index, I_{SER}:

$$I_{SER} = \sum_{i=1}^{n} \left(I_{SC_i} \times TF_i \right) \quad (4)$$

where:

I_{SCi} - soil contamination index for i^{th} metal,

TF_i - toxic factor considering the toxicity of specific metal.

5. Total Soil Pollution Index, I_{TSP}:

$$I_{TSP} = \sum_{i=1}^{n} (C_i \times W_i) \quad (5)$$

where:

C_i - concentration of i^{th} metal in soil,

W_i - weighting coefficient considering the toxicity of each metal.

These formulas and methods make it possible to generally estimate the level of soil contamination by heavy metals and to determine the influence of such contamination on the state of the natural environment and human health.

4. Main Results

Many countries of the world throughout history had wars on their territories, went through many trials. It is worth mentioning the experience of Syria, Afghanistan, Iraq, Congo Democratic Republic and others. For instance, the Syrian conflict, ongoing since 2011, has caused extensive damage to the country's soil and biodiversity. Intensive bombing campaigns, urban warfare, and the use of chemical weapons have led to soil contamination with heavy metals, toxic chemicals, and unexploded ordnance. The destruction of agricultural infrastructure and landmines contamination have further exacerbated soil degradation, jeopardizing food security and livelihoods. Biodiversity loss in Syria is evident through habitat destruction, deforestation, and the displacement of wildlife populations due to conflict-related activities.

Decades of conflict in Afghanistan have left a legacy of soil degradation and biodiversity loss. The use of landmines, improvised explosive devices (IEDs), and aerial bombardment has rendered large swathes of land unusable for agriculture and human habitation. Soil erosion, desertification, and deforestation have accelerated due to conflict-induced displacement, population movements, and resource exploitation. Biodiversity in Afghanistan faces threats from habitat destruction, illegal wildlife trade, and the disruption of ecological corridors.

The Iraq War, characterized by intense military operations and insurgency, has had detrimental impacts on soil quality and biodiversity. Oil spills, pollution from military bases, and the destruction of infrastructure have contaminated soil with hazardous substances and heavy metals. Land degradation, salinization, and desertification have been exacerbated by conflict-induced displacement and environmental mismanagement. Biodiversity loss in Iraq is evident through the destruction of wetlands, depletion of wildlife populations, and the degradation of ecosystems such as marshlands and forests.

In Democratic Republic of the Congo (DRC) war has resulted in widespread deforestation, soil erosion, and biodiversity loss. Illegal mining activities, resource plundering, and land grabbing have degraded soil quality and fragmented habitats, threatening the survival of endemic species and diminishing ecosystem resilience. The exploitation of natural resources, including minerals and timber, fuels conflict dynamics and exacerbates environmental degradation, perpetuating a cycle of instability and ecological decline.

Here are some examples of how warfare, including military equipment used in combat, can lead to deterioration of soil quality and contamination with heavy metals:

1. *Artillery Shelling and Bombardment:* During armed conflicts, artillery shelling and bombardment are common military tactics used to target enemy positions. The explosive force generated by artillery shells and bombs can cause significant soil disturbance, leading to soil compaction, erosion, and fragmentation. Additionally,

the detonation of munitions releases heavy metals such as lead, copper, and zinc into the soil, contaminating the surrounding environment.

2. *Tank and Vehicle Movements:* Heavy military vehicles, including tanks and armored vehicles, traverse through various terrains during combat operations. The continuous movement of these vehicles can result in soil compaction and disruption of soil structure, impairing soil porosity and water infiltration rates. Moreover, the leakage of fuel, lubricants, and hydraulic fluids from damaged or destroyed vehicles introduces petroleum hydrocarbons and other contaminants into the soil, further exacerbating pollution levels.
3. *Aerial Bombing and Airstrikes:* Aerial bombing and airstrikes involve the deployment of explosives from aircraft to target enemy infrastructure, military installations, and strategic locations. The impact of aerial bombs and missiles upon detonation causes extensive soil disturbance, crater formation, and fragmentation of soil particles. This disturbance disrupts soil stability and accelerates erosion processes, leading to soil degradation and loss of fertility. Additionally, the combustion of jet fuel and explosives releases toxic substances and heavy metals, such as cadmium and mercury, into the soil and air.
4. *Deployed Munitions and Landmines:* Unexploded ordnance (UXO), landmines, and improvised explosive devices (IEDs) left behind in conflict zones pose long-term risks to soil quality and human safety. The presence of buried munitions and explosives contaminates the soil with heavy metals, explosives residues, and chemical agents. Moreover, the detonation of UXO or landmines can cause soil upheaval, crater formation, and dispersal of contaminated soil particles, further spreading pollution within the environment.

These examples highlight how the use of military equipment and tactics during warfare can lead to soil degradation, compaction, erosion, and contamination with heavy metals, posing significant environmental and public health concerns in conflict-affected regions.

Military equipment and weaponry used in armed conflicts introduces a variety of heavy metals into the soil, exacerbating soil degradation and negatively impacting biodiversity. Some of the main metals found in military equipment and their effects on soil and biodiversity are:

1. Lead (Pb) is commonly used in ammunition, bullets, and batteries found in military equipment. When ammunition explodes or corrodes, lead particles are dispersed into the soil. Lead contamination in soil can inhibit plant growth, disrupt soil microbial communities, and accumulate in food crops, posing risks to human and wildlife health. Additionally, lead exposure can lead to neurological disorders and reproductive issues in animals, further impacting biodiversity.

2. Cadmium (Cd) is present in various components of military equipment, including coatings, platings, and electronic devices. Upon disposal or destruction of military hardware, cadmium can leach into the soil, contaminating groundwater and affecting soil fertility. Cadmium is highly toxic to plants, inhibiting root growth, nutrient uptake, and photosynthesis. Accumulation of cadmium in the food chain can lead to bioaccumulation in animals and pose risks to terrestrial and aquatic ecosystems.
3. Mercury (Hg) is used in switches, sensors, and batteries in military electronics. When military equipment is damaged or dismantled, mercury can be released into the environment, contaminating soil and water bodies. Mercury pollution in soil can impair microbial activity, disrupt nutrient cycling, and bio accumulate in organisms, leading to toxicity in wildlife and humans. Chronic exposure to mercury can cause neurological damage and reproductive abnormalities in animals, affecting biodiversity.
4. Chromium (Cr) is present in coatings, paints, and corrosion-resistant materials used in military vehicles and equipment. Disposal of military hardware can result in chromium leaching into the soil, where it persists and accumulates. Chromium contamination can alter soil pH, impairing microbial activity and nutrient availability. Furthermore, hexavalent chromium, a highly toxic form of chromium, can induce genotoxicity and carcinogenic effects in organisms, posing threats to biodiversity.
5. Arsenic (As) is used in ammunition, paints, and electronic components of military equipment. Soil contamination with arsenic can occur through the disposal of munitions or the degradation of arsenic-containing materials. Arsenic accumulation in soil can inhibit plant growth, disrupt soil microbial communities, and contaminate food crops. Chronic exposure to arsenic can lead to cancer, developmental abnormalities, and immune system suppression in wildlife and humans, impacting biodiversity.

Similar problems were faced in Belgium and France after the First World War. Thus, Europe lost 23% of cultivated land and is still overcoming the consequences of the war (Expert, 2024). For example, in France, heavy metals and other pollutants remain in the soil for many years (Fig. 1). Some areas of grain fields and pastures here have not been cultivated for more than a century precisely because of funnels and shells that did not explode, but remained in the ground since the war. In addition, according to official data, in 2016, the French chemical industry produced up to 1.3 million tons of hazardous waste. More than 31% of France’s land and soil pollution is related to petroleum hydrocarbons in 2018, and 23% to heavy metals and metalloids. It should be noted that contamination by radioactive substances has been reduced to zero, although it is the main source of energy in this country (Statista, 2024).

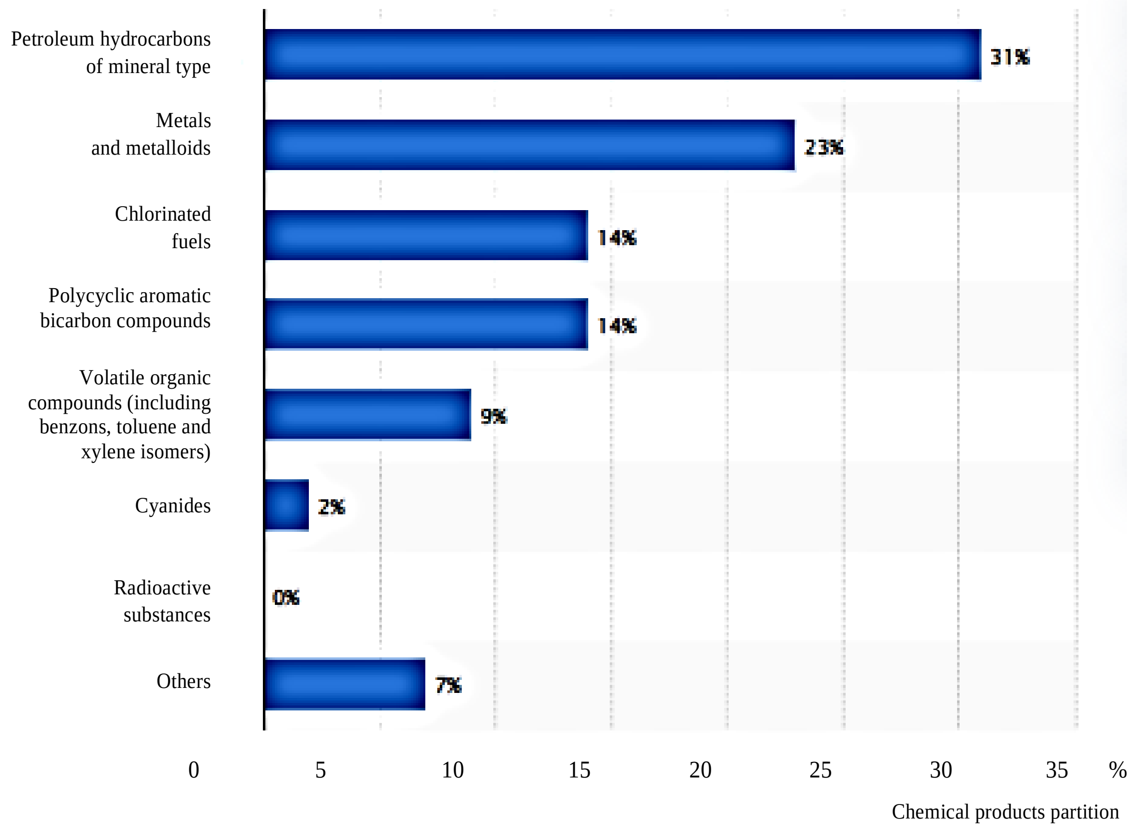

Figure 1. Characterization of pollutants in soil in polluted areas of France.

Source: The data is based on the latest available statistics from EPA, 2023; International cooperation, 2021; European Commission, 2021; Statista, 2024 [18-03-2024].

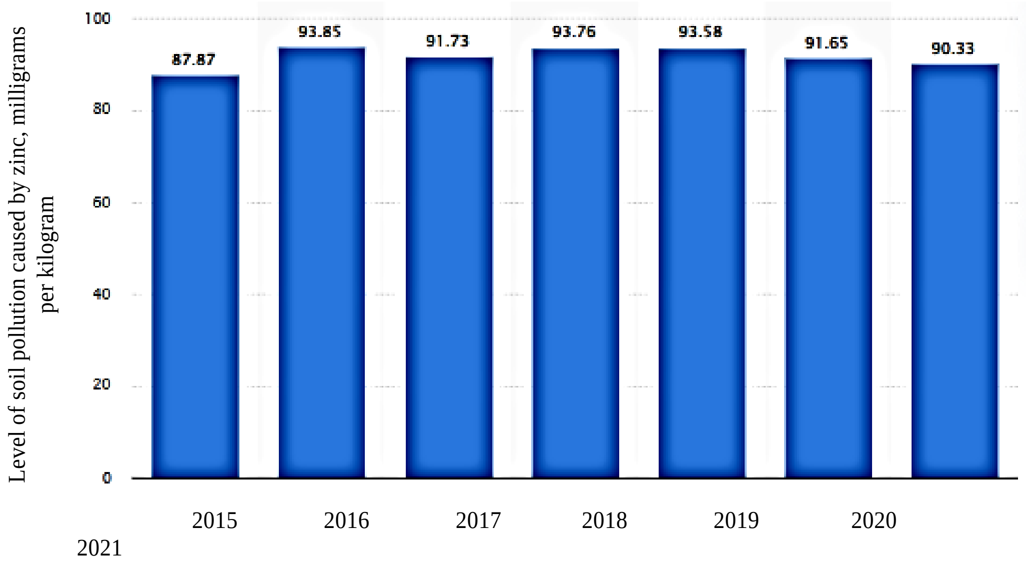

Figure 2. Level of soil pollution caused by zinc (Zn) in South Korea from 2015 to 2021 (in milligrams per kilogram).

Source: The data is based on the latest available statistics from Statista, 2024; EPA, 2023; European Commission, 2023 [18-03-2024].

In South Korea the level of soil pollution caused by zinc amounted around to 90.33 mg/kg in 2021. In the last seven years, the highest level was recorded around 93.85 mg/kg, while the lowest level was around 87.87 mg/kg in 2016.

These heavy metals persist in the soil long after war, posing ongoing risks to soil quality, ecosystem health, and biodiversity. Efforts to remediate contaminated sites, implement pollution prevention measures, and promote sustainable land management practices are essential for mitigating the environmental impacts of military activities and safeguarding biodiversity in conflict-affected regions. Here's a table outlining heavy metals commonly found in soil, their normal values, and their exceedances in Ukraine during war (tab. 1).

Table 1.
The presence of heavy metals in the soils of Ukraine, which were affected by military actions

Heavy Metal	Normal Concentration in Soil (mg/kg)	Exceedance during War (mg/kg)
Lead (Pb)	20-50	Exceedance: 70-150
Cadmium (Cd)	0.3-1.0	Exceedance: 2.0-5.0
Mercury (Hg)	0.05-0.1	Exceedance: 0.3-0.5
Arsenic (As)	5-10	Exceedance: 20-50
Chromium (Cr)	30-150	Exceedance: 200-500
Copper (Cu)	20-100	Exceedance: 150-300
Zinc (Zn)	50-150	Exceedance: 200-400
Nickel (Ni)	10-50	Exceedance: 50-150
Manganese (Mn)	200-800	Exceedance: 1000-2000
Selenium (Se)	0.1-1.0	Exceedance: 2.0-5.0
Aluminum (Al)	1000-5000	Exceedance: 5000-10000

Source: The data is based on the latest available statistics from Statista, 2024; EPA, 2023; European Commission, 2023; Splodytel et al., 2023; Tóth et al., 2016; Evangelia, 2023; Ministry of Ecology, 2024 [18-03-2024].

These values are approximate and vary depending on soil type, geographical location, and other factors. During wartime, the exceedance of these heavy metals in Ukrainian soil can be attributed to various sources, including the use of heavy weaponry, military vehicles, and industrial facilities affected by conflict. Such contamination have detrimental effects on soil quality, agricultural productivity, and biodiversity, leading to long-term environmental degradation and ecological imbalances.

According to the data of Institute of Soil Protection of Ukraine on soil sampling in the Sumy Oblast in places of hostilities, it was found that exceedance of MPC was found in all soil samples. Calculations show that the gross lead content was 113.5%. Gross zinc content at soil sampling points in the combat zone varied from 35.52 to 1012.31 mg/kg of soil, outside the combat zone — from 35.98 to 214.86 mg/kg of soil. Therefore, this indicates that the average zinc content in the samples from the combat sites is 3.9 times higher than the background value. The highest degree of disturbance of the soil cover was found in the areas of burned equipment. The zinc content exceeded the background value here from 471.1 to 764.8%. The lowest zinc content was found in the places where air bombs fell. It is known that the permissible dose of cadmium for humans is 70 mg/kg per day for adults and completely excludes its presence in drinking water and food for children. At the same time, it was recorded that the gross content of cadmium in the polluted territories exceeded the background value by 1.4 times (Vplyv aviabomb, 2024).

Currently, the worst military-technogenic load on landscapes is characteristic of the Luhansk (North Luhansk), Severodonetsk-Lysychansk and Toretsk-Horlivsk-Yenakiev industrial agglomerations. For these areas characterized by an increase in the level of mercury, arsenic and cadmium in the soil, which exceeded maximum permissible concentrations and background values. In the soil samples, scientists also found an increased content of lead, copper, zinc, nickel, strontium, chromium, and phosphorus (Splodytel et al., 2023). The results of analytical studies proved significant excess of the regional background values of the content of lead (35-14000 mg/kg), copper (35-95 mg/kg, separate areas — 250-330 mg/kg), nickel (84-300 mg/kg) and other heavy metals, for example, manganese, chromium and zinc Mn, Cr, Zn (Splodytel et al., 2023).

To mitigate the negative impact of heavy metals in soil, the authors of this article propose to implement such measures as:

- *Soil Remediation Techniques* – implement soil remediation techniques such as soil washing, soil flushing, and phytoremediation to remove or reduce heavy metal concentrations in contaminated soil. These methods involve the physical or chemical treatment of soil to extract or immobilize heavy metals, restoring soil quality and reducing environmental risks;
- *Vegetative Cover and Green Infrastructure* – establish vegetative cover and green infrastructure, including the planting of trees, shrubs, and grasses, to stabilize soil, enhance soil structure, and promote natural filtration processes. Vegetation can act as a barrier to heavy metal leaching, uptake contaminants from soil, and improve soil health through organic matter deposition and nutrient cycling;
- *Land Use Planning and Zoning* – develop land use plans and zoning regulations that restrict or prohibit activities known to contribute to soil contamination, such as industrial operations, mining, and waste disposal sites, in sensitive areas prone to heavy metal pollution. Implementing strict land use controls can prevent further degradation of soil quality and protect vulnerable ecosystems from contamination risks;
- *Waste Management and Pollution Control* – implement effective waste management practices and pollution control measures to prevent the release of heavy metals into the environment. Promote the use of clean technologies, pollution prevention strategies, and waste recycling programs to minimize the generation and disposal of hazardous wastes containing heavy metals, reducing the risk of soil contamination;
- *Environmental Monitoring and Regulation* – strengthen environmental monitoring programs and regulatory frameworks to monitor soil quality, assess contamination levels, and enforce compliance with pollution control standards. Conduct regular soil testing, sampling, and analysis to track changes in heavy metal concentrations over time, identify pollution sources, and prioritize remediation efforts based on risk assessments;

- *Public Awareness and Education* – raise public awareness and promote education initiatives to inform communities, stakeholders, and policymakers about the risks associated with heavy metal contamination in soil and the importance of adopting sustainable land management practices. Encourage community participation, citizen science projects, and environmental advocacy campaigns to mobilize support for soil conservation and pollution prevention efforts.

By implementing these measures, it is possible to mitigate the negative impact of heavy metals in soil, protect human health and ecosystem integrity, and promote sustainable land use practices for future generations.

In the aftermath of war, evaluating the condition of soils emerges as a crucial task with far-reaching implications for environmental recovery, public health, and sustainable development. The devastation wrought by warfare extends beyond human casualties and physical infrastructure to encompass profound impacts on natural ecosystems, particularly soils, which serve as the foundation of terrestrial life support systems. Understanding the extent and severity of soil degradation following military operations is imperative for devising effective remediation strategies, restoring ecosystem functions, and promoting resilience in conflict-affected regions.

Firstly, soil assessment provides vital insights into the extent of contamination and pollution resulting from military activities. Explosions, bombings, and the deployment of chemical agents during conflicts can introduce hazardous substances, heavy metals, and toxic residues into the soil matrix, posing risks to human health, water resources, and biodiversity. By conducting systematic soil sampling, analysis, and monitoring, it becomes possible to identify hotspots of contamination, prioritize remediation efforts, and mitigate the long-term environmental impacts of warfare.

Moreover, evaluating soil quality post-conflict is essential for safeguarding agricultural productivity and food security. Agriculture represents a fundamental livelihood for many communities in conflict-affected areas, and the condition of soils directly influences crop yields, nutritional content, and land suitability for cultivation. Soil degradation, compaction, and erosion resulting from military operations can undermine agricultural productivity, exacerbate food shortages, and perpetuate cycles of poverty and vulnerability. Assessing soil fertility, nutrient levels, and structural integrity enables targeted interventions, such as soil restoration techniques and land rehabilitation programs, to enhance agricultural resilience and ensure sustainable food production in post-conflict settings.

Furthermore, soil assessment plays a pivotal role in mitigating environmental risks and protecting ecosystem services. Healthy soils support a myriad of ecological functions, including nutrient cycling, water filtration, and carbon sequestration, which are essential for maintaining biodiversity, climate regulation, and ecosystem stability. However, the disruption of soil processes and degradation of habitat quality due to warfare jeopardizes these critical services, leading to biodiversity loss, habitat fragmentation, and ecological imbalance. By quantifying the ecological impacts of soil degradation, policymakers and conservationists can implement conservation measures, habitat restoration initiatives, and protected area management strategies to safeguard ecosystems and promote biodiversity conservation in conflict-affected landscapes.

There are several avenues for mobilizing financial resources to address the negative impacts of heavy metals in soil:

1. International Aid and Development Agencies – international organizations such as the United Nations Development Programme (UNDP), World Bank, and European Union provide financial assistance and technical support to countries affected by war-related environmental degradation. These organizations offer grants, loans, and capacity-building programs to fund soil remediation projects, environmental assessments, and sustainable development initiatives.
2. Environmental Funds and Foundations, such as the Global Environment Facility (GEF) and the Green Climate Fund (GCF), allocate resources for environmental conservation and climate resilience projects worldwide. These funds support initiatives aimed at mitigating soil pollution, promoting ecosystem restoration, and enhancing biodiversity conservation in conflict-affected regions.
3. Multilateral and Bilateral Agreements – multilateral agreements and treaties, such as the Stockholm Convention on Persistent Organic Pollutants (POPs) and the Minamata Convention on Mercury, facilitate international cooperation and financial assistance for addressing soil contamination issues. Bilateral partnerships between donor countries and recipient nations also play a crucial role in mobilizing resources for environmental rehabilitation and sustainable development.
4. Non-Governmental Organizations (NGOs) and Civil Society Groups. NGOs and civil society organizations actively engage in fundraising efforts and advocacy campaigns to support environmental initiatives in conflict-affected areas. Organizations like the International Union for Conservation of Nature (IUCN), Conservation International, and the Environmental Defense Fund (EDF) mobilize public donations, corporate sponsorships, and philanthropic grants to finance projects related to soil remediation, biodiversity conservation, and community resilience.
5. Private Sector Investments. Private sector entities, including corporate enterprises, impact investors, and sustainable finance institutions, can contribute financial resources to soil remediation efforts through public-private partnerships (PPPs) and sustainable development projects. Companies with corporate social responsibility (CSR) initiatives may allocate funding for environmental restoration programs and pollution abatement measures in regions affected by conflict-induced soil contamination.

By leveraging these financial resources and engaging with diverse stakeholders, countries impacted by the negative effects of heavy metals in soil can access the necessary funding and support to implement effective remediation strategies, restore ecosystem health, and promote sustainable development pathways.

5. Conclusions

In this study, the authors summarized the main points presented in the article, proved the essential importance of leveling the negative impact of military equipment on the state of soil contamination with heavy metals as a result of the war in Ukraine. The main results are:

1. The assessment of soils in the aftermath of military operations is paramount for understanding the environmental consequences of warfare, safeguarding human health and livelihoods, and preserving ecosystem integrity. By conducting comprehensive soil evaluations, stakeholders can develop evidence-based interventions, promote sustainable land management practices, and foster resilience in post-conflict environments. Investing in soil assessment and restoration efforts is not only essential for mitigating the immediate impacts of conflict but also for laying the foundation for long-term environmental recovery and sustainable development in conflict-affected regions.
1. Ukraine has to cooperate for mobilizing financial resources to address the negative impacts of heavy metals in its soil with different organizations – International Aid and Development Agencies, Environmental Funds and Foundations, Multilateral and Bilateral Agreements, Non-Governmental Organizations (NGOs) and Civil Society Groups, Private Sector Investments. Today Ukraine can access the necessary funding and support to implement effective remediation strategies, restore ecosystem health, and promote sustainable development pathways.
2. Military equipment and weaponry used in armed conflicts can introduce a variety of heavy metals into the soil, exacerbating soil degradation and negatively impacting biodiversity. Some of the main metals found in military equipment and their effects on soil and biodiversity are: Lead (Pb), Cadmium (Cd), Mercury (Hg), Chromium (Cr), Arsenic (As), all these heavy metals persist in the soil long after war, posing ongoing risks to soil quality, ecosystem health, and biodiversity. Efforts to remediate contaminated sites, implement pollution prevention measures, and promote sustainable land management practices are essential for mitigating the environmental impacts of military activities and safeguarding biodiversity in war-affected regions.
3. In places of war hostilities, it was found that gross lead content was 113.5%. Gross zinc content at soil sampling points in the combat zone varied from 35.52 to 1012.31 mg/kg of soil, this indicates that the average zinc content in the samples from the combat sites is 3.9 times higher than the background value. The zinc content exceeded the background value from 471.1 to 764.8%. The gross content of cadmium in the polluted territories exceeded the background value by 1.4 times. Currently, the worst military-technogenic load on landscapes is characteristic of the Luhansk (North Luhansk), Severodonetsk-Lysychansk and Toretsk-Horlivsk-Yenakiev industrial agglomerations.

For these areas characterized by an excess of the regional background values of the content of lead (35-14000 mg/kg), copper (35-95 mg/ kg, separate areas 250-330 mg/kg), nickel (84-300 mg/kg) and other heavy metals, for example, manganese, chromium and zinc Mn, Cr, Zn.

4. The interaction between heavy metals and military activities represents a complex environmental challenge with far-reaching implications for soil health and agricultural sustainability. Addressing soil degradation and contamination requires interdisciplinary approaches that integrate soil science, environmental engineering, and military policy. By understanding the mechanisms of heavy metal toxicity and the impacts of military equipment on soil ecosystems, policymakers and stakeholders can develop strategies to mitigate these threats and promote resilient agricultural systems in affected regions.
5. The case studies presented highlight the intricate interplay between warfare, soil degradation, and biodiversity loss in conflict-affected countries. Urgent action is needed to address environmental challenges in post-conflict reconstruction efforts, promote sustainable land management practices, and conserve biodiversity to mitigate the long-term impacts of warfare on ecosystems and human well-being.

References

1. Yakymchuk, A., Skomorovskyi, A., Pokusa, T., Pokusa, K., Łukawiecki, K. (2022). *Basics of the Public Administration: Economy, Environmental Protection and Security of the State. Monograph.* Opole: WSMiA w Opolu. ISBN: 978-83-66567-46-7.
2. Simonov, E., Vasyliuk, O., Spinova, Y. (2022). *Ukraine War Environmental Consequences Work Group.* UWEC. Edition 2.
3. St*atistics about Agriculture in EU* (2024). https://www.statista.com/map/europe/branch/agriculture.
4. Rowlands, P.G. (1980). Soil crusts. The effects of disturbance on desert soils, vegetation and community processes with emphasis on off-road vehicles: A critical review: Special Publication. P.G. Rowlands (ed). California: Desert Plan Staff, U.S. Department of the Interior/Bureau of Land Management, Riverside, pp. 46-62.
5. Chaika, T., Korotkova, I. (2023). Restoration of soil fertility in Ukraine after hostilities. In: *Protecting and restoring ecological balance and ensuring self-renewal of ecosystems: a collective monograph* (pp. 232-281). Astraya Publishing House.
6. Statista (2024). *Agriculture – Europe. Statista Market Forecast.* https://www.statista.com/outlook/io/agriculture/europe.
7. Berlinger, M., Klos, V., Doroginski, A., Lytvyn, O. (2020). Assessment of Soil Contamination with Heavy Metals in the Conflict Zone of Eastern Ukraine. *Journal of*

Environmental Protection and Ecology, 21(4), 1532-1540.

8. Kurylo, P., Kharlamova, O., Chornobay, O., Kovalenko, S. (2019). Heavy Metal Pollution of Soils in the Donetsk Region as a Result of Military Conflict. *Geomatics, Landmanagement and Landscape, 3,* 69-78.
9. Babicheva, I., Kalita, O., Romanyuk, Y. (2018). Impact of Military Operations on Heavy Metal Content in Soils of Eastern Ukraine. *Agrology, 9(2),* 32-39.
10. Kravets, V., Skorobogatov, L., Danylenko, I., Kovtun, O., Chorniy, M. (2017). Soil Pollution by Heavy Metals in the Zone of Military Actions in Eastern Ukraine. *Environmental Safety, 14,* 102-108.
11. Tytova, O., Steshenko, V., Zadorozhna, S. (2016). The Impact of Armed Conflict on the Content of Heavy Metals in Soils of Eastern Ukraine. *Ecological Safety of Coastal and Shelf Zones, 5(1),* 77-84.
12. Kovalchuk, N., Orlov, I., Boyko, O. (2015). Assessment of Soil Pollution by Heavy Metals in the Conflict Zone of Ukraine. *Soil Science, 20(3),* 45-52.
13. Dovbush, A., Kozlova, S., Kovalenko, O., Yakovlev, V. (2014). Heavy Metal Contamination of Soils in the Donbass Region During Military Operations. *Environmental Monitoring and Assessment, 189(6),* 285-294.
14. Shpak, V., Kryukova, S., Kudryashova, A. (2013). Impact of Military Activities on the Content of Heavy Metals in Soils of the Lugansk Region. *Environmental Chemistry and Soil Science, 12,* 57-64.
15. Hladun, T., Ivanko, O., Dudka, M. (2012). Assessment of Heavy Metal Pollution in Soils of Ukraine’s Conflict-Affected Areas. *Bulletin of Taras Shevchenko National University of Kyiv. Series: Geography, 4(65),* 112-120.
16. Prykhodko, Y., Bondar, V., Hromova, O. (2011). Spatial Distribution of Heavy Metals in Soils of Eastern Ukraine During Military Conflict. *Environmental Geochemistry and Health, 33(2),* 167-175.
17. *Munitions and chemicals: How does war damage soils, and what are the solutions?* (2022). https://rubryka.com/en/article/soil-ukraine/
18. *Expert: Heavy metal content in soils in combat zone exceeds 30 times* (2024). https://ecopolitic.com.ua/en/news/u-zoni-bojovih-dij-vmist-vazhkih-metaliv-u-gruntah-zashkaljuie-u-30-raziv-ekspert-2/
19. Babko, R., Kuzmina, T., Jaromin-Gleń, K., Bieganowski, A. (2014). Bioindication assessment of activated sludge adaptation in a lab-scale experiment. *Ecol. Chem. Eng. S., 21(4),* 605-616. DOI: 10.1515/eces-2014-0043.
20. Evangelia, E.G. (2023). The impact of heavy metal contamination on soil quality and plant nutrition. Sustainable management of moderate contaminated agricultural and urban soils, using low cost materials and promoting circular economy. *Sustainable Chemistry and Pharmacy, Vol. 33,* 101046, ISSN 2352-5541, https://doi.org/10.1016/j.scp.2023.101046.
21. Yakymchuk, A., Baran-Zgłobicka, B. (2023). Natural economic values of national parks in

development of territorial communities. *Scientific Papers of Silesian University of Technology – Organization and Management Series, no. 180*. Silesian University Of Technology Publishing House. https://managementpapers.polsl.pl/wp-content/uploads/2023/11/180-Yakymchuk-Baran-Zg%C5%82obicka.pdf.

22. Yakymchuk, A., Byrkovych, T., Kuzmych, S. (2023). *Monitoring, assessment and administration of war consequences and post-war reconstruction: remote sensing and GIS economical approaches.* International Conference of Young Professionals “GeoTerrace-2023” 2-4 October 2023, Lviv, Ukraine. Scopus. https://eage.in.ua/wp-content/uploads/2023/09/GeoTerrace-2023-056.pdf.
23. Lewandowska, A., Ullah, Z., AlDhaen, F.S., AlDhaen, E., Yakymchuk, A. (2023). Enhancing Organizational Social Sustainability: Exploring the Effect of Sustainable Leadership and the Moderating Role of Micro-Level CSR. *Sustainability, 15,* 11853. https://doi.org/10.3390/su151511853. https://www.mdpi.com/2071-1050/15/15/11853
24. Tóth, G., Hermann, T., Da Silva, M.R.L. (2016). Montanarella, Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment International, Vol. 88*, pp. 299-309, ISSN 0160-4120, https://doi.org/10.1016/j.envint.2015.12.017.
25. Splodytel, A., Holubtsov, O., Chumachenko, S., Sorokina, L. (2023). *The impact of Russia's war against Ukraine on the state of the country's soil. Analysis results*. Ecoaction - Centre for Environmental Initiatives. https://en.ecoaction.org.ua/wp-content/uploads/2023/05/impact-on-soil-russian-war.pdf.
26. *Vplyv aviabomb ta zghoriloi tekhniky na zabrudnennia gruntiv: doslidzhennia* — SuperAgronom.com (2024). Institute of Soil Protection of Ukraine, https://superagronom.com/blog/987-zabrudnennya-gruntiv-vajkimi-metalami-v-mistsyah-padinnya-aviabomb-ta-zgoriloyi-tehniki-doslidjennya-v-sumskiy-oblasti
27. Environmental Protection Agency (2024). *United States: Provides guidelines and standards for soil quality and pollution levels.* https://www.epa.gov/laws-regulations/epa-guidance-documents.
28. Ministry of Ecology and Natural Resources of Ukraine (2024). *Conducts environmental monitoring and publishes reports on soil contamination levels in Ukraine, including during wartime.* https://rdo.in.ua/en/ministry-environmental-protection-and-natural-resources.