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Environmental consequences of military operations in Ukraine on the example of soil research in the Kharkiv region

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Abstract. The paper considers the main aspects of the impacts of military activities on soils, including changes in the hydrological regime, contamination, and destruction of soil structure. The article highlights the environmental hazards of military activities in Ukraine, based on the results of laboratory studies of the soil samples collected in the areas of Kharkiv Oblast that have been affected by military operations, namely areas with burnt-out military equipment or impact sites of aircraft bombs and artillery shelling. It was confirmed that military operations lead to significant chemical pollution of soils with heavy metals due to explosions, combustion of military equipment, and leaks of industrial chemicals. This pollution negatively affects the ecosystems by reducing soil fertility and disrupting plant growth. Moreover, toxic compounds accumulate in the food chains, posing risks to human health. The authors emphasize the need for further research and measures to clean up and restore the polluted soils so as to minimize the environmental consequences of the war. The article examines the contribution of hostilities in Ukraine in the period from 2022 to 2024 to the chemical contamination of the soils with heavy metals. The main sources of the pollution were analyzed, including the degradation of munitions, combustion of military equipment, and explosions of shells and missiles. The results of the laboratory studies conducted in Kharkiv Oblast showed that the contents of lead, copper, and zinc in the soils significantly exceeded the background levels and maximum permissible concentrations. In particular, the average lead content in the areas of hostilities was 2.8 times higher than the MPC. The concentration of zinc was three times higher than the background levels and 1.2-1.4 times higher than the MPC. The average content of copper was 1.45 MPC, exceeding the MPC in 7 out of 10 plots. The article highlights the negative impact of chemical pollution on biodiversity, plant and animal health, as well as risks to human health due to bioaccumulation and biomagnification of heavy metals in the food chain. The high coefficient of variation of heavy metal content in the soil samples indicates a significant unevenness of the pollution, which requires further research to develop effective measures for cleaning and restoring contaminated soils.

Keywords: military operations, Ukraine, environmental hazard, heavy metals, soils.

Екологічні наслідки бойових дій в Україні на прикладі дослідження ґрунтів Харківського регіону

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Анотація. Розглянуто основні аспекти впливу бойових дій на ґрунти, зокрема забруднення, зміну гідрологічного режиму та руйнування структури ґрунту. Висвітлено екологічну небезпеку бойових дій на території України, проаналізовано результати лабораторних досліджень проб ґрунтів, відібраних на землях Харківського регіону, які постраждали унаслідок ведення бойових дій, а саме ділянки із згорілою військовою технікою або ділянки після обстрілу арилерійськими снарядами та авіабомбами. Підтверджено, що бойові дії призводять до значного хімічного забруднення ґрунтів важкими металами через вибухи, згоряння військової техніки та витоки промислових хімікатів. Це забруднення негативно впливає на екосистеми, знижуючи родючість ґрунтів, порушуючи ріст рослин та акумулюючи токсичні речовини у харчовому ланцюзі, що створює ризики для здоров'я людей. Акцентована увага на необхідності подальших досліджень та заходів з очищення та відновлення забруднених ґрунтів для мінімізації екологічних наслідків війни. У статті розглядається вплив бойових дій в Україні в період з 2022 по 2024 роки на хімічне забруднення ґрунтів важкими металами. Аналізуються основні джерела забруднення, серед яких руйнування боєприпасів, згоряння військової техніки та вибухи снарядів і ракет. Представлені результати лабораторних досліджень, проведених у Харківському регіоні, свідчать, що вміст свинцю, міді та цинку у ґрунтах суттєво перевищує фонові рівні та гранично допустимі концентрації. Зокрема, середній вміст свинцю у ділянках бойових дій у 2,8 рази перевищує ГДК. Концентрація цинку утричі перевищує фонові значення та у 1,2–1,4 рази перевищує ГДК. Середній вміст купруму становить 1,45 ГДК, спостерігається перевищення ГДК у 7 з 10 ділянок. Висвітлено негативний вплив хімічного забруднення на біорізноманіття, стан рослин і тварин, а також ризики для здоров'я людей через біоакумуляцію та біомагніфікацію важких металів у харчовому ланцюзі. Високий коефіцієнт варіації вмісту важких металів у зразках ґрунтів свідчить про значну нерівномірність забруднення, що потребує подальших досліджень для розробки ефективних заходів з очищення та відновлення забруднених ґрунтів.

Ключові слова: бойові дії, Україна, екологічна небезпека, важкі метали, грунти

Introduction

The Russian military aggression against Ukraine has caused destruction of the infrastructure, mass migration, and human casualties, and also has had a deleterious impact on the environment. Military activities, which plagued a large portion of the country, have led to long-term ecological changes, detrimental to the population's health. Assessment of such ecological consequences is an important objective to follow in order to minimize their impact on affected areas.

Study of ecological consequences of military activities is crucial for several reasons:

- preserving health of the population, mitigating far-reaching negative effects of contaminations of soil, water and air, including heightened levels of morbidity
- restoring ecosystems, understanding the scale and pattern of ecological damages, which is necessary to design effective strategies for remediation and rehabilitation of affected ecosystems;
- preventing further degradation of the ecosystems, because studies of impacts of military activities on the environment can identify the most sensitive components that require measures to thwart exacerbation;
- studying the contribution to global climate change and thus, effects on biodiversity;
- developing ecological policy and legislation (Krukov, 2020) oriented at the protection of environment during armed conflicts, based on results of research.

Thus, studying ecological implications of the war in Ukraine is extremely important to provide a sustainable development, preserve health of the population, and restore the country's nature.

Disturbances of soil caused by war are mostly the physical, chemical, and biological (Certini, 2023). Physical disturbances of soil are associated with construction of defensive lines and fortifications, digging trenches, compaction as a result of movement of heavy equipment, and craters from shelling. Chemical disturbances include influx of pollutants, such as petroleum products, heavy metals (HMs), nitroaromatic explosives, organophosphate nerve agents, dioxins, and radioactive elements. Biological disturbances stem from changes in the physical-chemical properties of soil and loss of humus.

Operational areas were found to contain HMs, most of them (Pb, Hg, As, Cd, Cu, and Ni) usually occuring in heightened concentrations (Broomandi, 2020). However, a mobile form, rather than general concentraton, is the one to consider, since during changes in the conditions (such as soil pH, acid rain, floods, which alter redox potential), poorly soluble compounds of HMs can transform into mobile forms (Buts, 2018, 2019, 2020).

Implications of the large-scale war that Russia has started severely lack research. The knowledge of soil disturbance resulting from military actions is slowly expanding, although there is a need to further study this issue using phytoremediation and monitoring of HM migration from minefields and territories affected by artillery shelling and bombardment (Stadler Tamas, 2022).

In 2022-2024, military actions have inflicted irreparable harm to the Ukrainian ecosystems, including soil. Indeed, war not only physically destroys soil but also chemically contaminates it. Shells, destroyed military equipment, and petroleum products foul the ecosystems, especially soils and aquatic objects (Bezsonnyi, 2021). Some of the most dangerous soil contaminants are HMs: lead, copper, mercury, arsenic, nickel, and zinc. These HMs enter the environment with residues of ordnance that contain high concentrations of metal particles, and also as a result of using artillery, grenades, and missiles.

Contaminations with HMs can retain for many years, because they form insoluble oxides and hydroxides and accumulate in soils (Buts, 2018, 2019, 2020; Krainiuk, 2023), compromising their fertility (Zaitsev, 2022).

Studies of soil contamination in conflict areas, such as Iraq (Zhiltsov, 2023) and Afghanistan (Hashimy, 2023), revealed a significantly elevated levels of HMs, including Pb, Cu, Zn, Hg, Cd, Ni, and As, thereby corroborating that military activities are a major source of pollution.

The results of studies on shooting ranges in China confirmed that contamination with HMs, in particular, Pb, Cu, Hg, and Sb, in the soil have relatively high potential ecological risks (Bai, 2020).

In Ukraine, single studies were conducted in Luhansk (north Luhansk), Sieverodonetsk-Lysychansk, and the Toretsk-Horlivka-Yenakievo industrial agglomerations, identifying excessive concentrations of HMs compared with the background values, in particular 7.6 times for Zn, 1.4 times for Cd, and 1.1 times for Pb (Yakymchuk, 2024).

The analysis of soil in Lviv after a missile strike revealed that in all the soil samples, the levels Ti, Zn, Pb, and Ni were significantly higher than maximum permissible concentrations (MPCs). There was confirmed a high effectiveness of extraction of Zn, Cu, Cr, and Cd from soil by the plants (Petrushka, 2024).

Military actions in Ukraine have caused a significant degradation of soils due to mechanical disturbance by heavy equipment, contaminations with debris of armament, munitions, and residues of fuels and lubricants. The studies by Solokha et al. (2024) revealed significant changes in the structure and composition of soil fractions, accompanied by reduced microbiological activity and high toxicity. The analysis of contents of heavy metals (Pb, Zn, and Cd) confirmed their accumulation in the upper soil layers, which causes physical-chemical degradation and negatively affects the condition of the agroecosystems. Based on the obtained results, the authors introduced a new term – «soil degradation caused by military actions», which encompasses losses of mechanical, physical, chemical, biological, and physical-chemical properties of the soil cover (Solokha, 2022).

Similar consequences were also observed in other regions of Ukraine. Thus, a study by Datsko (2024) revealed that an intensive bombardment of agricultural lands in Sumy and Chernihiv oblasts have caused local increases in the concentrations of Ba, Zr, Rb, Zn, and V. However, the general tendencies do not point to a significant contamination, which complicates a complex assessment of impacts of military actions on the condition of soils. At the same time, in the Kyiinka territorial community of Chernihiv Oblast, active military engagement has affected 44 ha of the soil cover, while the general ecological and economic losses were estimated as 192.2 M hryvnias (Bonchkovskyi, 2023). Using satellite images, there were determined zones of bombturbation and contamination levels that varied depending on the intensity of military actions.

A large-scale mapping of Kharkiv Oblast (Bonchkovskyi, 2025) allowed finding over 420,615 craters and over 3,411 ha of soil that has been mechanically damaged from movements of heavy equipment. Despite insignificant concentrations of heavy metals in most of the samples, critical levels of contamination were found in the places of missile impacts and aircraft crashes, which present additional risks to the environment. Also, special attention was paid to assessing the likelihood of contamination of soils with explosive objects and unexploded ordnance.

The analysis of geochemical composition of the soils in Chkalivske territorial community of Kharkiv Oblast (Smirnova, 2024) revealed an insignificant increase in the concentrations of heavy metals, which, nonetheless, is not critical for agriculture. In the study, the processes of natural attenuation of the soils were assessed and possible methods of their recultivation were analyzed. In general, military actions significantly affect the stability of soil cover, altering its physical, chemical, and biological properties. High contents of toxic compounds and increased acidity of soils were observed in the areas of active military actions, and an extensive contamination with fuels and lubricants have led to death of flora and fauna, except for the species that are resistant to extreme conditions (Biyashev, 2024).

Despite a large number of conducted studies, assessment of impacts of war on the condition of soil remains fragmented. Splodytel (2023) emphasized the necessity of further complex geochemical studies and development of methods of monitoring and ecological restoration of affected territories.

Objectives of the study

Therefore, the objectives of our study were assessing the impacts of military actions on the level of contamination of soils with heavy metals, analyzing the disturbance of soil cover, caused by the war, and predicting possible risks associated with the degradation and contamination of soils.

Materials and methods

The concentrations of heavy metals were analyzed using a flame atomic absorption spectrophotometer (AAS). The experimental study was carried out at the Laboratory of Ecological-Analytic Studies of the analytic center Ukrainian Scientific Research Institute of Ecological Problems.

The contents of total concentrations of the HMs were determined according to DSTU ISO 11047. The obtained results were compared with the maximum permissible concentrations (MPCs) according to the Normative of Maximum Permissible Concentrations of Hazardous Compounds in Soils (Order of Cabinet of Ministers of Ukraine № 1325).

For the study, we collected soil samples during expeditions to different districts of Kharkiv Oblast that have been affected by military actions. From each crater caused by explosion, we collected 3-4 samples from different zones – the floor and the rim. Later, those samples were unified for the formation of mean sample value, which was used for further analysis. In total, we formed 10 average samples that represented the condition of the soils in the affected areas. The selection was performed from the upper 20 cm layer of soil according to the standard methods of ecological monitoring and assessment of contamination.

For the background values, we collected samples of soils from the areas located at a 200 m distance from the areas affected by shell explosions. The collection of the background samples was carried out in the areas with a similar type of land use, which allowed adequately comparing results and assessing the effects of military actions on the chemical composition and physical-chemical properties of the soils.

The data were collected from September 2022 to July 2024.

Results and analysis

Below are the main aspects of the impacts of military actions on soils, including physical disturbance, chemical contamination, biological impact, and disturbed hydrological regime, with examples and con-

Table 1. Sampling of the soils for chemical analysis from the locations affected by military actions in Kharkiv Oblast

№ of sample	Location	Description	Type of land use	Form of relief	Morphometric parameters of the affected zones
1	Velykyi Burluk	Place of mass destruction of military equipment	Agricultural field	Watershed plain	Impact area: ~0.1-0.3 ha
2	Staryi Saltiv	Impact sites of aerial bombs/shells	Windbreak near a field	Slope	Crater diameter: 5 m
3	Kupiansk	Place of mass destruction of military equipment	Meadows, open space	Watershed plain	Impact area: ~0.3-0.4 ha
4	Kupiansk	Impact sites of aerial bombs/shells	Agricultural field	Slope	Crater diameter: up to 6 m
5	Borova	Place of mass destruction of military equipment	Forest zone	Terrace	Impact area: ~0.2-0.3 ha
6	Izium	Place of mass destruction of military equipment	Windbreak, forest outskirt	Watershed plain	Impact area: ~0.3-0.5 ha
7	Savyntsi	Place of mass destruction of military equipment	Agricultural field	Watershed plain	Impact area: ~0.2 ha
8	Balakliia	Impact sites of aerial bombs/shells	Forest zone	Slope	Crater diameter: 4-6 m
9	Kharkiv (the Kharkiv Ring Road, Pivnichna Saltivka)	Impact sites of aerial bombs/shells	Residential area, roadside	Watershed plain	Crater diameter: 3-4 m
10	Kharkiv (the Kharkiv Ring Road, Piatyhatky)	Impact sites of aerial bombs/shells	Forest-park	Slope	Crater diameter: 3-4 m

sequences for the environment, agriculture, and socioeconomic sphere (Table 2).

1. Military activities can substantially alter the hydrological regime of soil, which manifests in several key aspects presented in Table 3.

2. Contamination of fertile layer of soil can be a result of shell explosions and leakages of contaminants, which considerably reduce the humidity and fertility of the soil and induce other destructive processes.

3. Movement of military equipment results in soil compaction that limits the ability of plants to effectively use available aquatic resources and adapt to changes in the water balance.

4. Another cause of changes in the hydrological regime of soil is large fires occurring due to military actions (Krainiuk et al. 2024). To analyze forest fires, along with decrease in vegetation and changes in NDVI indices, we used satellite images (EO Browser).

Table 2. Impacts of military actions on the soils (developed by the authors)

Aspects of impact	Details	Examples	Implications
Physical damages to soil	Craters from explosions	Explosions of artillery shells, missiles, and aerial bombs leave craters of up to several meters wide, causing dynamic soil compaction and disturbance of the soil horizons.	Degradation of the soil profile, mixing of the genetic horizons. Changes in the physical properties of soil, formation of post-war landscapes with new types of microrelief (Baliuk, 2023).
	Soil compaction	Soil compaction due to movement of heavy equipment (tanks, APCs).	Decrease in soil aeration, deterioration of water permeability, degasification of soil.
	Mechanical damage	Construction of defensive positions, digging tranches or tunnels, fortifications, defensive lines, etc.	Degradation of the soil profile, disruption of geomorphologic processes, movements of soil, landslides, soil subsidence.
Chemical contamination	Contamination with petroleum products, heavy metals, and other toxicants	Contaminations due to explosions (heavy metals, explosives, polycyclic aromatic hydrocarbons, nitroaromatic explosives, organophosphate nerve agents (Certini, 2013).	Long-term contamination of soil, decrease in its fertility, impact on plants and animals, potential necessity of complete replacement of soil in polluted areas (Baliuk, 2024).
	Formation of military-technogenic geochemical abnormalities due to accumulation of explosive and other toxic agents (Splodytel, 2023).		
	Settlement of products of munition combustion, which contain nitrogen, soot, carbon, manganese, and lead.	In Iraq due to using cluster munitions, ~1,730 km^2 of land were contaminated (Splodytel, 2023).	High risks to the health of people due to contact with contaminated soils and inhalation of toxic compounds.
	Radioactive contamination	Using depleted uranium munitions.	Long-term radioactive contamination, risks to the health of people and environment.
Biological impact	Loss of fertility	Contamination with chemicals, soil compaction.	Decrease in yields of agricultural crops.
	Loss of biodiversity	Degradation of natural habitats.	Decline in species diversity, decimation of endemic plants and animals.
	Impact on soil microorganisms	Decline in the number of beneficial soil microorganisms, disturbance of the biological activity of soil.	Decrease in the effectiveness of natural attenuation of soils, decline in fertility.
	Introduction of dangerous microorganisms	Intentional or accidental introduction of microorganisms that can retain their virulence in soil (Baliuk, 2024).	Long-term danger to the ecosystem and people, complication of soil rehabilitation.

Продовження табл. 2

Mechanical erosion	Wind erosion	Ruination of the superficial layer of soil.	Loss of the upper fertile layer of soil, degradation of lands, deflation, spread of dust storms.
	Water erosion	Annihilation of vegetative cover.	Increase in the risk of soil washout, deterioration of soil quality.
Disturbance of hydrological regime	Soil compaction	Movement of heavy equipment, explosions.	Decrease in water permeability, increase in surface runoff.
	Damage to drainage systems	Ruination of canals and drainage systems.	Flooding of fields, water stagnation, waterlogging, secondary salinization.
	Changes in the streambeds of rivers and water bodies	Explosions, soil displacement.	Change in the direction of water runoff, flooding or drying of territories.
	Contamination of aquatic objects	Chemicals and heavy metals.	Decline in the quality of water, contamination of groundwater.
Disturbance to ecosystems	Change in the ecological balance	Military actions alter the energy exchange and other natural processes.	Disturbance of the stability of ecosystems, decline in the productivity.
	Loss of natural resources	Destruction of natural landscapes.	Decline in the availability and quality of natural resources.
Socioeconomic consequences	Decrease in the productivity of agriculture	Large minefields.	Deterioration of food safety, economic losses.
	Forced migration of population	Contaminated and degraded soils.	Forced migration, social issues
Positive effect (Certini, 2013)	Soil fertilization	Introduction of N and P through explosions, use of explosives as fertilizers.	Improvement of some physical properties of soil, promotion of growth of some plants.
	Formations of natural reservoirs of biodiversity	Korean Demilitarized Zone, areas with low level of human activity (Natura 2000).	Preservation of biodiversity, restoration of natural ecosystems.

On the bright side, there are studies mentioning some possible positive effects of military actions on soil, in particular, due to establishment of «neutral» territories, such as demilitarized zones that can promote a restoration of biodiversity, and also using craters for fish breeding (Certini, 2013). Military zones within the Natura 2000 network can indeed preserve biodiversity, but in general, harm that military actions impose on soil and ecosystems is overwhelming. Making prognoses for future consequences for soil is hard, but it can be expected that they will be long-lasting and devastating, with degradation of soil and pollution that affect fertility.

We should take into account that the natural rate of restoration of fertile layer of soil is very slow. A legacy on the environment is an enduring remnant of war, and restoration of soils can take much time and considerable efforts.

According to the Ukrainian Prime Minister, in Ukraine, Russia has laid the world's largest minefield. Over 30% of the country has been mine-laden (YONHAP NEWS AGENCY, 2023), and the area of potentially mine-infested land accounts for 250, 000 km^2.

Chemical contamination of the Ukrainian soils is a serious ecological footprint of the war. The sources of chemical contamination of soil during war include:

1. Residues of explosive agents (United States Environmental Protection Agency, 2006) that can contain toxic components that contaminate soil (residues of munitions, bullets, shell fragments, mines). Those residues often contain HMs, such as lead, copper, and zinc, which seep into soil.

2. Combusting military equipment and petroleum products that enter the soil.

3. Chemical compounds from warehouses and industrial enterprises, leakages of industrial chemicals from damaged infrastructure.

Among the chemical contaminants, we should distinguish:

- Heavy metals (lead, copper, and zinc): they are toxic to plants and animals and can accumulate in living organisms, leading to various diseases, including disorders of the nervous system and kidneys.
- Organic contaminants: polycyclic aromatic hydrocarbons (PAHs), which can form during combus-

Table 3. Impacts of military actions of the hydrological regime of soil (developed by the authors)

Key aspects	Details	Implications
Changes in the water permeability and water retaining capacity of soil	Soil compaction. Explosions, movement of heavy military equipment, and construction of temporary military infrastructure (trenches, fortifications) cause soil compaction, and thus, reduced soil permeability. The inability of water to infiltrate deep into the soil profile means increase in surface runoff. As a result, moisture evaporates in large amounts, instead of feeding the groundwater. As the amount of water that usually penetrates down to the level of groundwater shrinks, the level of groundwater declines over time (Perkins, 2007).	Deterioration of the conditions for plants, decrease in the level of groundwater, increase in the risk of erosion.
	Damage to the soil structure. Explosions ruin soil aggregates, thereby reducing its ability to retain water. Therefore, soil quickly dries out after rains, which reduces the amount of moisture available to the plants.	Decline in the soil fertility, deterioration in the conditions for agricultural crops.
Disturbance of drainage systems	Damage to the natural and artificial drainage systems. Military activities can ruin natural and man-made drainage systems (ditches, water divides), thereby disrupting the natural water runoff. This can lead to water stagnation in the fields, flooding of agricultural lands, and intensification of waterlogging processes. The effect of secondary salinization. Deterioration of the drainage causes accumulation of moisture in the soil layers, leading to elevation of groundwater. If these waters contain soluble salts, evaporation of moisture from the surface causes deposition of salts in the root-containing layer. This can deteriorate soil quality, reduce its fertility, and negatively affect the agricultural crops.	Flooding of lands, deterioration of the conditions for farming, increase in the risk of waterlogging.
	Changes in the streambeds of rivers and water bodies. Explosions and movements of soil can alter the riverbeds of rivers and other water bodies, thereby disturbing their hydrological regime. This can change the direction of water flow, causing flooding and drying of certain areas.	Disturbance of ecosystems, changes in the landscape, increase in the risk of ecological disasters.
Contamination and its implications	Introduction of contaminants to water objects. As a result of military activities, soil and surface water are contaminated by various agents (heavy metals, chemical compounds from munitions and equipment). Those compounds can reach groundwater, thus compromising its quality and making water inappropriate for drinking and irrigation.	Contamination of water, deterioration of drinking water, increase in the risk to the health of people and animals.
	Decrease in the filtrating properties of soil. Contaminated and compacted soil is worse in filtrating water, which increases the risk of introduction of contaminated water to water bodies and groundwater. Mechanism of impact: Clogging of the pores – toxic particles fill in the pores, deteriorating the porocity and the filtrating properties. Change in the aggregate composition – chemical contamination leads to densification of the soil structure. Surface sealing – formation of a dense layer that hinders water infiltration Compaction of soil – impact of equipment and construction of fortifications reduce the porocity, hampering the water infiltration. Complex contamination worsens the filtration property of soil, thereby elevating the risks of water contamination (Certini, 2013).	Increase in the risk of contamination of water resources, deterioration of water quality.
Implications for agriculture and ecosystems	Decrease in the productivity of agricultural lands. Deterioration of the hydrological regime of soil worsens the conditions for the growth of agricultural crops. This can manifest in water deficiency during dry periods and overly wet seasons, which decreases the yields and increases the risks of no yields.	Decrease in the yields, deterioration of the economic conditions of agrarian sector.
	Changes in ecosystems. Changes in the hydrological regime of soil can negatively affect the ecosystems, affecting plants and animals living in the area. This can lead to decline in the biodiversity and disruption in the ecosystem resilience.	Decrease in biodiversity, disturbance of ecological balance, increase in the risk of extinction of certain species.

tion of oil and coal. These compounds are carcinogenic and can persist in soil for a long time.
- Chemical residues of explosives, for example, nitroaromatic compounds that are toxic to living organisms.
- Petroleum products that reduce the fertility of soils and decrease the local flora and fauna.

Thus, the impacts of chemical contamination on the ecosystem include impairment of plant growth, reduction of soil fertility, degradation of ecosystems; death of microorganisms, which affect the self-cleaning of soil; and accumulation of toxic compounds in the food chain, which negatively affect human health (Table 4).

Therefore, we corroborated that during military actions, HMs and toxic compounds are emitted into the environment in large amounts. Such a contamination occurs due to explosions, degradation of munitions, combustion of military equipment, and other dangerous objects, etc. Heavy metals, such as lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), copper (Cu), nickel (Ni), and zinc (Zn) enter soil, augmenting the concentrations up to toxic levels.

There were reported cases of extreme pollution of soils with compounds of lead, for example, by Dinake (2020), who presented the results of analysis of the soil in a testing ground located in a military airbase south of Botswana, where the Pb concentration reached 38,406.87 mk/kg. In particular, the discovered general concentration of lead does not provide data on its bioavailability, mobility, and quantitative risk of environmental pollution to the biota, but proves that 65% of lead can become mobile and bioavailable chemical forms (Dinake, 2020).

Plants in military testing grounds and zones of military actions concentrate HMs. Such a conclusion was drawn by Busby et al. (2020), who studied plants from several military testing grounds in Alaska. On average, the herbaceous plants accumulated higher concentrations of Cr, Cu, Ni, Pb, Sb, and Zn, compared with shrubs, which, in turn, bioconcentrated higher concentrations of Sb.

The studies that we conducted in Kharkiv Oblast indicated the elevated levels of HMs in the soils in the areas of military operations (Fig. 1). In particular, the contents of lead (Fig. 1), cuprum, cadmium, and zinc in the soils were significantly higher than the background levels, indicating a substantial pollution caused by military actions.

The total contents of lead in the soil sampling points in the area of military actions varied 26 to 212 mg/kg of soil, whereas the background values ranged 9 to 30 mg/kg of soil (Fig. 1). Exceedances relative to the background values were noted for all the samples, and the average concentration of lead in the areas of military actions amounted to 90.3 mg/kg, which was 2.8 times above the MPC for the total concentration.

The coefficients of variation of the lead concentration accounted for 139.1% in the samples collected in the zone of military actions and 242.8% outside the affected zone (background values).

The total contents of cuprum compounds in the soil sampling points in the zone of military actions varied 56 to 288 mg/kg of soil, and the background values ranged 9 to 44 mg/kg of soil (Fig. 2). Exceedances relative to the MPC in the zones of military actions were seen in 7 of 10 plots, while the average content of cuprum was 1.45 times above the MPC.

The total contents of zinc in the studied soils, affected by military actions, ranged 96 to 418 mg/kg of soil, and the background values measured 38 to 176 mg/kg of soil (Fig. 3). Exceedances relative to the background values were observed in all 10 studied samples. The average content of zinc in the samples was 207 mg/kg, i.e. three times that of the background; and two samples exhibited values 1.2 and 1.4

Table 4. Table of the impact of chemical contamination of soil (developed by the authors)

Contamination source	Types of contaminants	Impact on soil and ecosystem
Remnants of explosives	Trinitroluene, nitroaromatic explosives (hexogen, octogen)	Toxic to plants and animals, long-term contamination of soil
Remnants of munitions	Lead (Pb), copper (Cu), zinc (Zn), cadmium (Cd), mercury (Hg)	Accumulation of heavy metals, toxicity to plants, animals, and people
Combustion of military equipment	Polycyclic aromatic hydrocarbons, benzo(a) oyrene, benz(a)anthracene, petroleum products (diesel fuel, oils)	Carcinogenic compounds, soil contamination, decline in fertility
Leakages from warehouses and enterprises	Industrial chemicals (sulfuric acid (H_2SO_4), nitric acid (HNO_3), chlororganic compounds)	Contamination of soil with toxic compounds, impact on groundwater
Products of combustion of rocket propellants	Hydrazine, dimethylhydrazine, hydrogen peroxide	Toxicity, carcinogenicity, contamination of soil, impact on water resources, long-term soil contamination

times above the MPC. The coefficient of variation of Zn was 197% in the samples from the area of military actions, and accounted for 159% for the background values.

Discussion

The analysis of the obtained results allows us to draw several important generalizations about the military pollution of soil:

1. General tendencies. At the sites of burnt-out equipment (plots 1, 3, 5, 6, and 7), the concentrations of heavy metals were typically higher than at the sites of craters after artillery shelling (plots 2, 4, 8, 9, and 10). Similar results were yielded in the study by Solokha (2024). Thus, the concentrations of Pb in the soil were 4-7 times higher than the MPC, especially in plots 1 and 3, associated with destroyed equipment. Solokha et al. (2024) observed much higher content

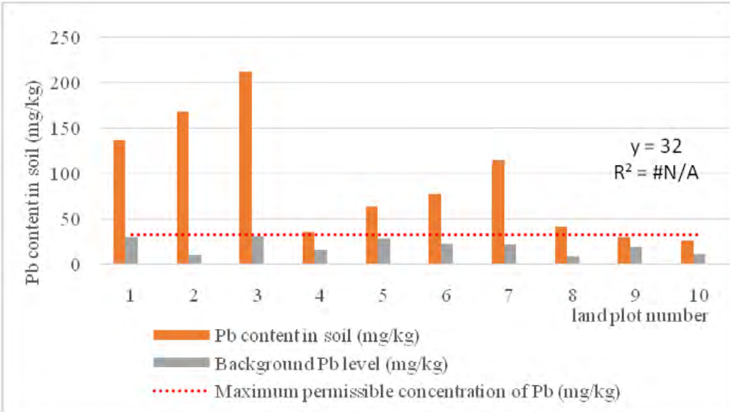

Fig. 1. The total concentrations of lead in the agricultural soils in Kharkiv Oblast that have been affected by military activities

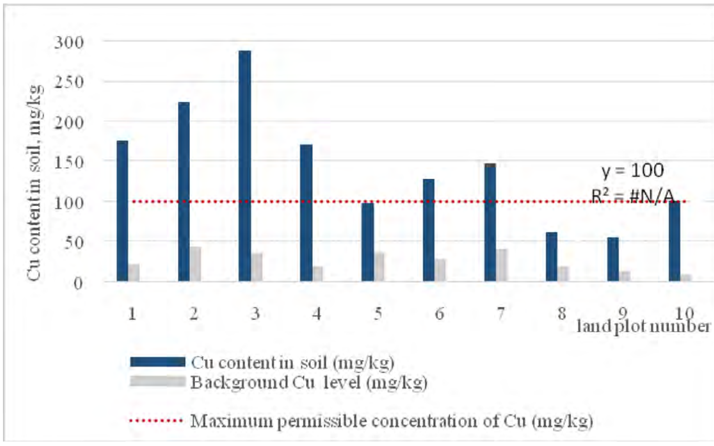

Fig. 2. The total concentrations of cuprum in the agricultural soils in Kharkiv Oblast that have been affected by military activities

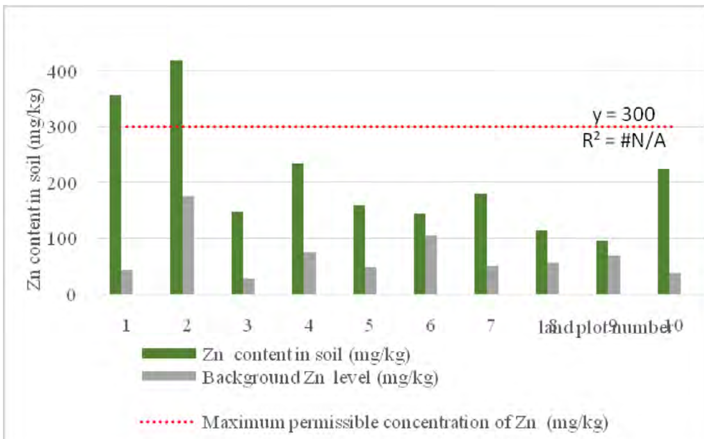

Fig. 3. The total concentrations of zinc in the agricultural soils in Kharkiv Oblast that have been affected by military activities

of lead (78.8 MPC). The content of Cu was above the MPC in almost all sample plots of destroyed equipment. The general level of Zn at the sites of destroyed equipment was also higher, although a much greater range was noted. In the samples analyzed by Solokha (2024), the zinc content reached 8.7 MPC.

2. Comparison between the locations of burnt-out equipment and craters from artillery shelling. The highest concentrations of Pb were recorded in the plots of burnt-out equipment (1, 3, and 7), indicating an additional pollution stemming from combustion of military machinery (Table 5). In the craters (artillery craters), Pb was also present, but its level was lower and could be derived mostly from residues of shells.

In the study by Baliuk S. (2023), the concentration of Pb was observed to gradually decline from the center of crater downward along the soil profile, but the concentration in most samples did not exceed the MPC. However, in the craters from 122 m caliber weapons, the level of Pb was elevated (23.4–23.6 mg/kg). The highest concentrations of Pb (Baliuk) were recorded at the localities of a helicopter crash (up to 1.6 Clark) and a recent strike with an X-55 rocket (up to 1.7 Clark).

In plots 1, 3, 5, 6, and 7 (burnt-out equipment), the concentration of Cu was 40% higher than in the craters. This can be explained by the fact that Cu is used in wiring, vehicle armor, and lubricants, which release Cu into the environment during combustion.

Our results are consistent with the studies by Zaitsev (2022), who also reported higher pollution with Cu in the locations of burnt-out equipment than in the craters. Interestingly, Baliuk et al. (2023) indicate higher content of Cu particularly in craters from explosions, especially in places of detonation of 152 mm caliber shells and missile impact sites. However, the highest concentrations of Cu (65.0–71.5 mg/kg) were observed in the place of the military helicopter crash. Perhaps, this is related to types of artillery shells and aerial bombs.

However, the general levels of Zn have been higher than the background values, and the difference between the sites of burnt equipment and craters was less expressed (9% higher in the locations of destroyed equipment). This could be attributed to the fact that Zn is a part of the shell casing, and also is used in metal alloys that burn in military equipment. Baliuk et al. (2023) observed the highest levels of Zn (107.4–114.2 mg/kg) in the place of the military helicopter crash.

Combustion of military equipment is a significant source of contamination with heavy metals, especially Pb and Cu. Shelling (craters) also causes contamination, but its impact is lower, since the main components of munitions are explosives and metals that remain in the soil after explosion for a shorter period. The greatest risk by Pb is presented on sites of destroyed equipment, because it is toxic to biosphere and can accumulate in plants and water.

The study by Splodytel (2023) also revealed an excessive Pb concentration in the soils contaminated as a result of military actions, and the authors recorded variability in the pollution levels depending on a type of military actions and location of sampling. Interestingly, Bonchkovskyi (2023) reported that the concentrations of heavy metals in most craters were only slightly above the background levels (1.1-1.5 times). However, at the sites of the military helicopter crash and a recent missile strike, the heavy metal pollution was observed to be critical.

To visually demonstrate the aforementioned, we used the method of boxplot diagram, which demonstrates the distribution of data, including median, quartiles, and possible outliers. It allows assessing the variation and asymmetry of the distribution.

Boxplot also facilitated the analysis of variations of the concentrations of heavy metals in the soil depending on the type of impact of military actions. The data were analyzed and visualized in the Python software, using the libraries Matplotlib and Seaborn, which allow developing scientific graphs and analyze the distribution of contaminants in soil (Fig. 4). This method is instrumental in assessing not only the average level of contamination but also the distribution of values, presence of outliers, and the range of variations. Boxplot comprises the following main elements:

- Interquartile range, IQR reflects the range between the 25th and 75th percentiles of the data, which includes the main portion of values.

- Median (black line inside an IQR) is a central value that divides the sampling in halves.

Table 5. Comparison between the sites of burnt-out equipment and craters from artillery shelling

Mean content, mg/kg	Places of burnt-out equipment (1, 3, 5, 6, and 7)	Craters from shelling (2, 4, 8, 9, and 10)	Difference
Pb	120.8	59.8	Twice greater in the places of burnt-out equipment
Cu	168.2	120.4	40% higher in the places of burnt-out equipment
Zn	197.4	181	9% higher in the places of burnt-out equipment

-Whiskers are the range of values measuring beyond 1.5×IQR.

-Outliers are the values that are significantly different from the general distribution.

The boxplot for lead demonstrates the significant exceedances of the maximum permissible level in all the examined plots; however, the maximum values were observed in the soil from the sites of burnt-out military equipment (points 1, 3, 5, 6, and 7). The median and the upper quartile are much higher in these samples compared with the craters from artillery shells. This corroborates that combustion of military equipment is a significant source of lead pollution.

Copper was characteristic of a significant variation in the values in the sites of destroyed equipment, with individual high concentrations (especially in points 1, 2, and 3). This could be a consequence of burning of copper alloys used in armor and electronic components of military vehicles. The craters from artillery shelling, although contained heightened levels of copper, demonstrated a lower amplitude variation.

The distribution of zinc also demonstrated the tendency towards elevated concentrations in the sites of burnt-out equipment, although the difference with the crater sites is less pronounced than in the cases of Pb and Cu. This is explained by a broad use of zinc coatings in military equipment.

The boxplot analysis clearly demonstrates that sites of destroyed equipment are a source of much greater heavy metal pollution than craters from artillery shelling. This is especially notable in the cases of lead and copper, indicating the necessity of additional research on the ecotoxic impact on the environment.

For a detailed study of the pattern of pollution of soils with heavy metals in the areas of military operations, we developed dispersion diagrams (Fig. 5), which allowed assessing possible patterns in the concentrations of lead (Pb), copper (Cu), and zinc (Zn). They were also developed using Python.

The dispersion diagram that reflects the relationship between the concentrations of Pb and Cu shows the tendency towards higher contents of both HMs in the places of burnt-out equipment, compared with the craters from artillery shelling. This could be due to the processes of thermal degradation of alloys in military equipment that contain substantial inclusions of Cu and Pb. A high correlation between these elements can point to their mutual source of contamination.

The diagram of the relationship between Pb and Zn demonstrates an uneven distribution of the concentrations, depending on a contamination source. In the places of destroyed equipment, the concentrations of lead and zinc were much higher, which could be explained by the use of these elements as materials for manufacturing of armed vehicles and electronic components. At the same time, in the samples collected in the craters from artillery shelling, the variability in the concentrations was lower, which can suggest another mechanism of contamination – emission of heavy metals from munitions and explosives.

The analysis of the ratio of Cu and Zn revealed a trend that is similar to the previous patterns, according to which the heightened concentrations of both metals were observed in the soil samples from the sites of destroyed equipment. This is consistent with the hypothesis about the technogenic origin of the pollution, because copper and zinc are broadly used in military manufacturing materials, electronics, and fuel systems.

The conducted analysis demonstrates that sites of destroyed equipment are much more polluted with heavy metals compared with sites of craters from artillery shelling. The correlation analysis indicated the presence of mutual sources of pollution with Pb, Cu, and Zn in such locations. These results confirm the hypothesis that it is combustion of military equipment that is the key factor of elevated levels of heavy met-

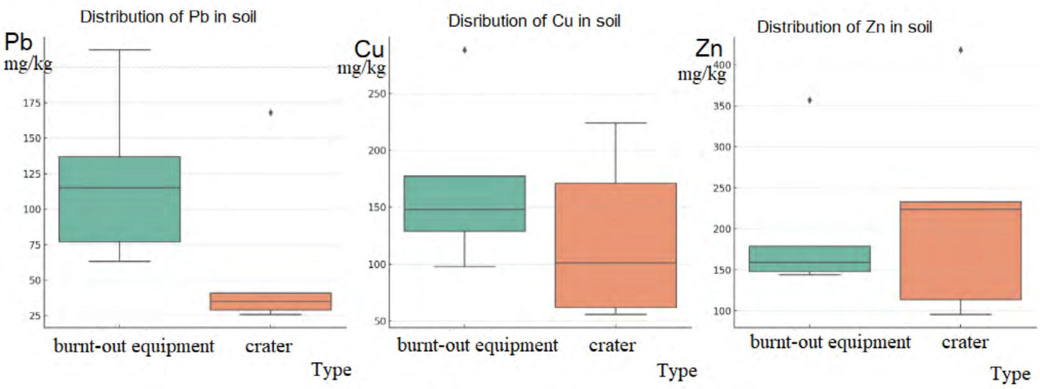

Fig. 4. Distribution of metals (Pb, Cu, Zn) in the soils that have been affected by military activities, according to type of impact

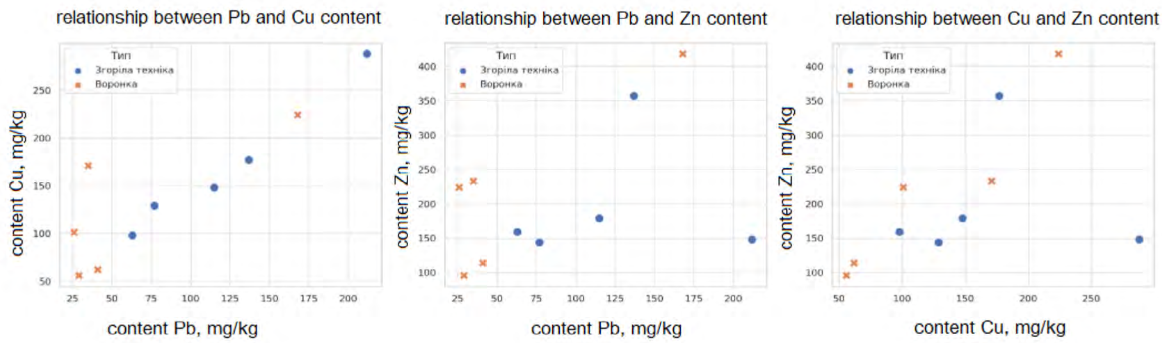

Fig. 5. Dispersion diagrams for comparison of the concentrations of heavy metals in the soils between the sites of burnt-out equipment and craters from artillery shells

als in soils, which can have long-term ecological implications.

Thus, the pollution with HMs caused by military operations in 2022-2024 is quite substantial and is related to degradation of munitions, combustion of equipment, and explosions of shells and missiles. The main heavy metal pollutants include lead, copper, and zinc. In our study, we conducted no radial analysis of the soil from the center of crater to its periphery. However, interesting are the results from Bonchkovskyi et al. (2023), who mentioned that the concentrations of HMs in most craters gradually decreased from the epicenter of explosion to the periphery, although in the places of helicopter crash or missile impact this decline was more rapid.

It has to be noted that besides metals examined in this article, soils in areas of military operations were also observed to contain such contaminants as Se, Sr, V, As (Bonchkovskyi, 2023), P and K (Solokha, 2024), and organic pollutants (Splodytel, 2023). In our following studies of the soils of eastern Kharkiv Oblast, we expanded the range of analyzed elements by including Zn, Pb, Hg, Cu, Fe, Cr, Ni, and Mn, a report on which will be published later.

Further persistence of high levels of heavy metals in the soils in the studied areas poses far-reaching ecological risks:

- decline in the fertility of the soils due to accumulation of toxic HMs, which will affect the yield of agricultural crops;
- expansion of toxic elements to food chains, which can negatively affect the health of people and animals;
- migration of contaminants to groundwater and surface water, which increases the risks for aquatic ecosystems and supply of drinking water;
- hindrance of natural restoration of soils, especially in areas with significant physical and chemical pollutions.

Recommendations regarding mitigation of the negative consequences can be as follows:

- monitoring and mapping of contaminated territories for determining the most affected zones and further prioritizing of cleanup measures;
- using technologies of recultivation of soils, including phytoremediation (using plants for removal of toxic metals), bioremediation (microorganisms), and mechanical removal of polluted soil layer;
- limitation of using polluted lands for agricultural needs until cleanup and restoration;
- creation of windbreaks and restoration of vegetative cover to minimize the risks of dissemination of toxic compounds and improvement of the condition of the soils;
- further studies of migration of contaminants and their impacts on ecosystems, which can help in adapting restoration strategies.

Conclusions

Military operations in Ukraine have serious and far-reaching impacts on soils, expressed in several aspects. Contamination of the fertile layer, degradation of its structure, and change in the hydrological regime negatively affect the environment, agriculture, and socioeconomic sphere. Military equipment and actions cause compaction of soil, decrease in its humidity, and deterioration of its structure, thereby limiting the ability of the plants to adapt and compromise the soil fertility. Another detrimental factor to the hydrological regime of soil is large fires caused by war.

Therefore, the main sources of HM contamination in areas of military operations are as follows:

- degradation of munitions (Pb, Cu, and Zn), because the cartridges and artillery shells are made using lead and copper, which are added to increase the mass and improve the aerodynamic properties;

- combustion of military equipment (Hg and Cd), since electronic components, batteries, and other devices contain mercury and cadmium;
- explosions of shells and missiles (Ni and As), because nickel and arsenic are used as stabilizers and additives for increasing the explosive power.

The studies indicated that the Pb concentration in the soils in the war zone in Kharkiv Oblast is 2.8 times above the MPC. The concentrations of Cu in the combat areas were observed to exceed the MPC in 7 out of 10 points, and the average concentration of Cu is 1.45 MPC.

The Zn concentration in the soil on average is three times higher than the background values, 1.2-1.4 times exceeding the MPC.

The average concentration coefficient (CC) for Pb equals 4.65, suggesting a significant excess relative to the background values. The maximum observed excess of Pb was 16.8 times (point 2). For Cu, the average coefficient of concentration is 5.37, and the maximum exceedance is eight times. The concentration of Zn in the soils on average exceeded the background values by three times (CC = 3.00), and in some points 9.5 exceedances were observed.

In the places of burnt-out equipment, the concentrations of heavy metals were the highest, highlighting the severity of ecological implications of military operations.

Therefore, restoration of soils is a complex and long process, especially taking into account the scales of mining, which poses a serious threat to the natural environment. Chemical pollution of soils with HMs, organic pollutants, and chemical explosive residues leads to degradation of ecosystems, disturbance of plant growth, and decline in the soil fertility. This is also negative for the health of people, as toxic compounds concentrate in food chains. We should emphasize the need for further research and effective measures for cleanup and restoration of the polluted soils in order to mitigate the negative impacts on ecosystem and human health.

Assessment of military degradation of soils can be an important tool for developing a strategy of restoring soil resources post-war, which would allow integrating those data into a strategy of ecological restoration of Ukraine.

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