ENVIRONMENTAL RISKS OF HEAVY METAL POLLUTION IN WAR-AFFECTED SOILS IN UKRAINE

LIUDMYLA YASHCHENKO[1], OLEKSANDR ANDROSHCHUK[2], LIUDMYLA VASYLENKO[3] AND YULIYA CHORNOIVAN[4,*]

[1] National University of Water and Environmental Engineering, Soborna St. 11, Rivne, Ukraine
[2] Institute of Agriculture of Western Polissia of the National Academy of Agrarian Sciences of Ukraine, Rivne St. 5, Shubkiv vill., Rivne dist., Rivne region, Ukraine
[3] Head of the Association of innovative laboratories, Office 1, Building 4-M, Lukasha M. str., Lviv, Lviv region, Ukraine
[4] Deputy General Director of Prime Lab Tech LLC, 115-V, Kyivskyi Shliakh str., Velyka Oleksandrivka vill., Boryspil District, Kyiv Region, Ukraine
* Corresponding author: office@plt.land

ABSTRACT

This study examines soil contamination by heavy metals in Ukraine resulting from military activities, focusing on three regions: Chernihiv (ChD), Sumy (SmD) and Dnipropetrovsk (DnD). These regions have varying technogenic backgrounds, affecting contamination levels. The aim was to assess concentrations of heavy metals (Cd, Cr, Pb, Cu, Ni, Mn, Zn) in soils affected by military actions and evaluate the associated environmental risks. Soil samples were collected from areas directly affected by explosions and from locations 500 meters away. Concentrations of heavy metals were compared with maximum permissible concentrations (MPC) and local geochemical background levels. The Environmental Risk Index (RI) was used to assess the risk of heavy metal accumulation. Results showed significant increases in metal concentrations in war-affected areas, with several metals exceeding MPC. The highest concentrations were recorded at DnD, where lead reached 3.9 MPC, nickel 1.8 MPC, and manganese 1.4 MPC. High levels of Pb and Ni were recorded at SmD, whereas at ChD high levels were only recorded for Pb and Ni. The RI for DnD and SmD was high (RI 391-324), indicating higher contamination and medium risk at ChD(RI 222). The environmemental risks in regions with high technogenic backgrounds, such as DnD, are more severe. This study underscores the importance of a technogenic background in contamination risks and the need for continuous monitoring and risk management strategies to protect ecosystems and human health.

Keywords: anthropogenic load; bombardment; environmental risk; heavy metals; military activities; pollution

Introduction

The war in Ukraine has attracted considerable attention from the scientific community due to its profound implications for environmental security, stemming from the widespread destruction of natural resources, ecosystems and infrastructure (Duiunova et al. 2024; Kharytonov et al. 2024; Wirtu et al. 2025). Armed conflict has large-scale effects on the natural environment, with soils being one of the most vulnerable components of the ecosystem. The use of modern military equipment, explosives, and ammunition, alongside large-scale air strikes have resulted in significant destruction and long-term environmental pollution. Consequently, it has become necessary to identify a distinct category of soil degradation caused by armed aggression, among which chemical pollution stands out as the most prolonged and hazardous effect, which poses a severe threat to human life (Baliuk et al. 2022).

In addition to natural sources, scientists and researchers have identified industrialization and urbanization, as well as the intensification of agricultural production through the widespread use of pesticides and fertilizers, as major contributors to heavy-metal contamination (Abdullahi et al. 2021; Rashid et al. 2023; Xu et al. 2023). However, in the context of military aggression and intensive use of weapons, the problem of additional soil contamination with heavy metals in Ukraine has become particularly acute. War affects every natural object, and the resultant pollution has long-lasting negative transboundary effects. Violations caused by war indicate that crimes against the environment, humanity, and war crimes disrupt the international balance, leading to dissonance in global international environmental security, thereby jeopardizing the right to a safe environment for future generations (Kharytonov et al. 2024).

Military activities during warfare alter soil properties, including pH, cation composition and humus content, which results in elevated heavy metal concentrations. These metals, such as Pb, Cu, Zn, Cd, and Ni are toxic, bioaccumulative and persistent, and pose significant risks to ecosystems and human health. For instance, Pb contamination can poison plants, animals and humans through the food chain. Similarly, metals in explosives or ammunition can disrupt soil processes, reduce fertility, and cause long-term degradation. As a result, war-affected soils may become unsuitable for agriculture, worsening environmental and economic effects. Understanding the toxic elements in the soil and assessing their distribution is crucial for both environmental protection and restoring agricultural productivity in post-war recovery (Dehtiarev et al. 2023).

Military operations involve the extensive use of various types of ammunition, which are significant sources

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of environmental pollution, particularly soil contamination. Modern ammunition comprises explosives, metal alloys and auxiliary materials that release a wide range of toxic substances during detonation. Most of these compounds are resistant to biodegradation or natural processing and thus persist in the biosphere and become long-term sources of pollution. These pollutants pose potential risks to human health and ecosystems because of their toxicity (Chaika and Korotkova 2023).

Gunpowder and explosives used in ammunition release chemical compounds that transform into gaseous and solid combustion products during detonation. While gases like nitrogen, carbon monoxide, and sulfur dioxide disperse into the atmosphere, most heavy particles settle on the soil. For example, detonating a 115 mm high-explosive projectile with hexogen produces up to 4,000 liters of gas, plus heavy metals. About 30% of these pollutants are released into the air, while the remainder accumulate in the soil and alter its chemical composition (Golubtsov et al. 2023). Greenhouse gas emissions are exacerbated by these activities (Pereira et al. 2022).

Metal compounds, such as lead (Pb), copper (Cu), cadmium (Cd), zinc (Zn) and manganese dioxide (MnO_2), are present in ammunition casings and are formed as by-products of explosive combustion (Makhovsky and Kriukovska 2015). Explosions also produce shrapnel, which scatters over hundreds of meters and gradually releases heavy metals as it decomposes in the soil. Lead and copper are among the primary compounds in ammunition (Greičiūtė et al. 2007), while zinc, often used to coat ammunition casings to prevent corrosion, and cadmium, chromium, and nickel, components of various alloys commonly occur in bombs (Yakymchuk et al. 2024).

The accumulation of these elements in the soil can exceed the natural background levels by tens or even hundreds of times, and the natural soil self-cleaning processes are extremely slow. These substances may decompose in the soil and migrate into groundwater, eventually entering food chains and affecting both humans and animals (Zaitsev et al. 2022).

Aerial bombs containing TNT, RDX, or other explosives release toxic metals like Ni and Cd, which are emitted during explosions. Fine particles containing these metals settle quickly on the ground, contributing to soil pollution. Once in the soil, these metals oxidize and enter environmental cycles, eventually reaching trophic chains. Contamination is further complicated by horizontal movement (via air transport) and vertical migration, influenced by ion diffusion, water flow, plant roots, soil fauna and human activity (Solokha et al. 2024).

This study aimed to evaluate the soil contamination caused by military operations in Ukraine, focusing on regions with varying industrial backgrounds. It specifically examines the concentrations of heavy metals in soils and compares them with maximum permissibles and geochemical background levels. Furthermore, this study assesses the potential environmental risks associated with heavy metal accumulation associated with the Russian military aggression in Ukraine. The findings will support the development of effective strategies to mitigate pollution and improve environmental conditions in affected regions.

Materials and Methods

For soil testing, sites were selected in areas directly affected by hostility, specifically where ammunition of various calibres had caused damage. Samples were collected from the impact zone and surrounding area in regions with varying initial anthropogenic loads: Chernihiv (51°59422″N 33°09458″E), location ChD, Sumy (50.86180″N 33.219175″E), location SmD, and Dnipropetrovsk (48°451465′N 35°176866′E), location DnD (Fig. 1). These locations were selected based on similar times for the bombardments (March–April 2023).

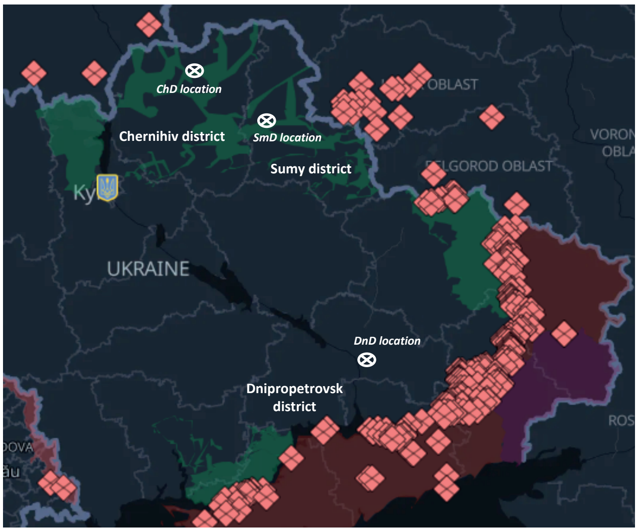

Fig. 1 Map of a Ukrainian conflict zone showing the locations of the sites where soil was sampled for analysis: Chernihiv (ChD), Sumy (SmD) and Dnipropetrovsk (DnD).

Soil sampling and analysis was carried out by the PRIME Lab Tech, LLC agrochemical laboratory (https://plt.land/uk), a facility specializing in high-precision soil analysis and expert recommendations for efficient land resource management. PRIME Lab Tech, LLC, is accredited under the DSTU EN ISO/IEC 17025:2019 standards (equivalent to EN ISO/IEC 17025:2017 and ISO/IEC 17025:2017, IDT) and holds the Accreditation Certificate No. 201741.

Two zones were identified around craters in order to characterize the effects of munitions on the soil.

1. Bombardment zone: the area directly affected by the explosion.
2. Contamination zone: the broader region influenced by weapon fragments and secondary pollutants (Bonchkovskyi et al. 2023).

In this study, soil samples collected from bombardment zones, that is, areas directly impacted by explosions, were designated as Ca (Fig. 2). For the contamination zone, the relationships between the aea of the bombardment zone, crater diameter and weapon fragment range followed that described by Sydorenko and Azarov (2007) – Table 1. Based on this framework, the soil samples collected 500 m from the epicenter of the damage were classified as not directly affected by bombardment. These samples were presumed to contain heavy metals originating primarily from other sources, such as the anthropogenic background (Cf).

Table 1 Average diameter of the contamination zone of various explosive weapons.

Weapon calibre, mm	Average diameter of the contamination zone, m
82, 76, 85, 100	20
120, 122	30
152, 140, 160	50
203, 220, 240	70
Aerial bombs	100

Sampling involved averaging the soil from Ca and along the perimeter of a concentric circle at a radius of 500 m from Cf collected from the 0–10 cm soil layer (Fig. 2), in accordance with DSTU ISO 10381-2:2004 Soil Quality sampling. Part 2. Guidelines for Sampling Methods (ISO 10381-2:2002, IDT) (Splodytel, 2023). Pretreatment of the samples for physicochemical analysis followed the ISO 11464:2007 standard. Prior to analysis, the composite samples were air-dried and sieved through a 0.25 mm mesh.

The total heavy metal content (Cd, Mn, Cu, Ni, Pb, and Zn) was determined after soil digestion using a mixture of acids (aqua regia) and dissolution of the residue in nitric acid, according to DSTU ISO 11466-2001 (equivalent to ISO 11466:1995 Soil Quality; Extraction of Trace Elements Soluble in Aqua Regia). The heavy metal concentrations were measured using inductively coupled plasma atomic emission spectrophotometry (ICPAES).

To evaluate the soil conditions, including the technogenic background and heavy metal content, in samples taken 500 m from Cf, the results were compared with the geochemical background values (Cgf) from the statistical parameters of heavy metal content in agricultural soils (Klos et al. 2012). The coefficient of the technogenic load (Kt), which is the heavy metal excess over the geochemical background, was calculated as follows (Equation 1):

$$Kt = \frac{Cf}{Cgf}, \tag{1}$$

where: Kt – the coefficient of the technogenic load, which is the extent of the excess of heavy metals over the geochemical background.
Cf – the technogenic background, which is the heavy metal content in soil samples 500 from the epicenter of an impact.
Cgf – the geochemical background value, which is the heavy metal content in agricultural soils.

To determine the accumulation of heavy metals resulting from military operations (Cw), the concentration

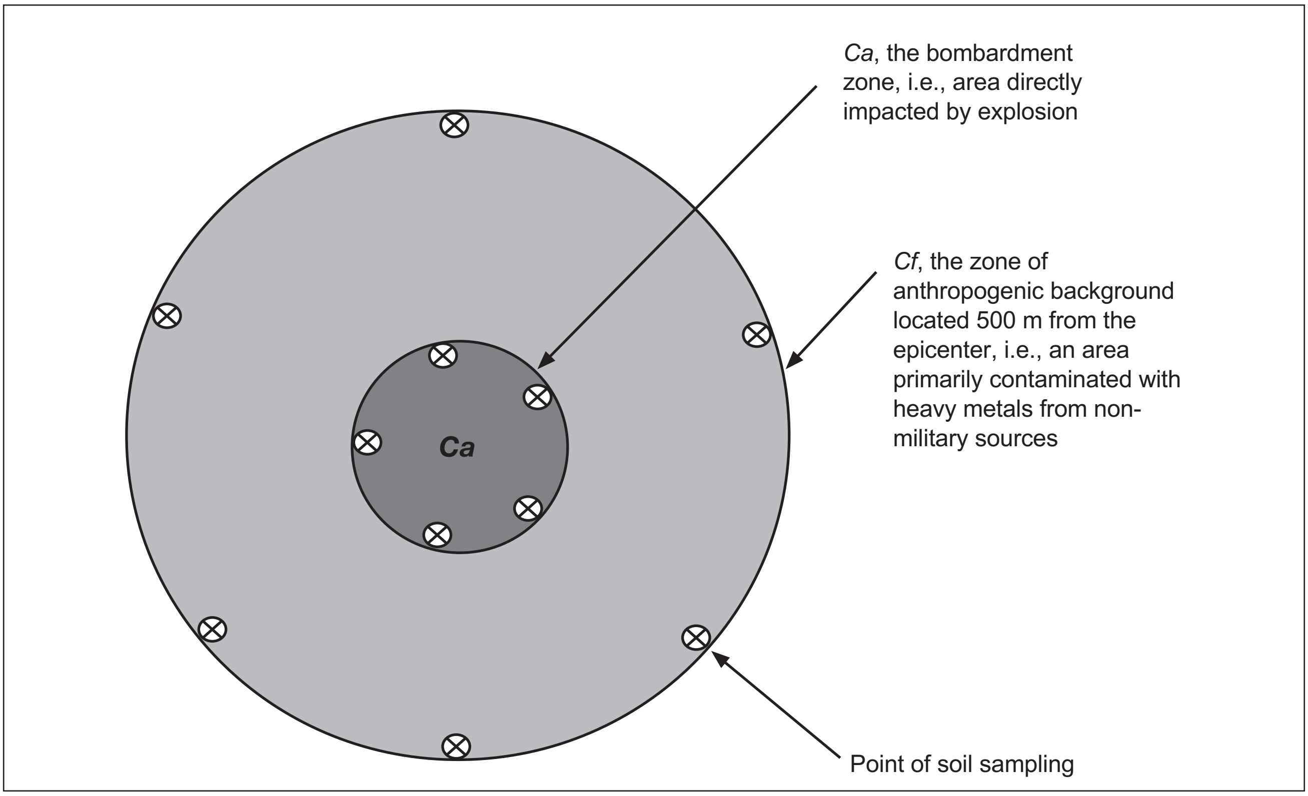

Fig. 2 Diagram of soil sampling design in a bombardment zone, which illustrates the spatial distribution of where soil was sampled within a contaminated area. The bombardment zone (Ca) is the area directly affected by the explosion, whereas the anthropogenic background zone (Cf) is the area 500 m from the epicenter, primarily containing heavy metals from nonmilitary sources. Soil samples were collected at the locations indicated for analysis.

at the impact point (Ca) was compared with the technogenic background (Cf) using Equation (2):

$$Cw = Ca - Cf, \tag{2}$$

where: Cw – the elemental content attributable to bombardment, mg/kg of soil.

Ca – the element concentration at the impact point, mg/kg of soil.

Cf – the technogenic background concentration, mg/kg of soil.

To assess the degree of soil enrichment with heavy metals due to bombardment, the concentration coefficient (Kc) was calculated, which is the ratio of the heavy metal content introduced during bombardment (Cw) to the technogenic background (Cf), as follows (Equation 3):

$$Kc = Cw - Cf, \tag{3}$$

where: Kc – the coefficient of soil enrichment with heavy metals.

The degree of soil enrichment with heavy metals (Kc) was assigned to one of four levels (Hakanson 1980; Malovanyy et al. 2024):

Kc < 1, no enrichment.

1 ≤ Kc ≤ 3: Moderate pollution.

3 ≤ Kc ≤ 6: Significant contamination.

Kc > 6: Very high pollution.

Calculations of the technogenic load (Kt), heavy metal accumulation due to bombardment (Cw) and the degree of soil enrichment (Kc) are critical for identifying the extent of environmental degradation in war-affected regions. These metrics provide essential data for prioritizing areas that require immediate remediation and support for informed decision making in environmental recovery efforts. Moreover, understanding heavy metal contamination levels helps assess the feasibility of restoring agricultural productivity in affected soils, ensuring food safety, and sustainable land use in the post-war period.

The potential risk index for each heavy metal was calculated, as follows (Equation 4).

$$E_r^i = T_r^i \times K_c^i, \tag{4}$$

where: K_c^i – the degree of metal enrichment as a result of bombardment.

T_r^i – the toxic reaction coefficient assigned to each heavy metal: Cd = 30, Pb = Ni = Cu = 5, Cr = 2, Zn, and Mn = 1 (Xu et al. 2008).

The integral value of the potential environmental risk (RI) was calculated as the sum of the potential risk indices for all heavy metals, as follows (Equation 5):

$$RI = \sum_{i=1}^{n} E_r^i \tag{5}$$

here E_r^i – is the potential risk index for each heavy metal.

The indices of potential risk for each element and integral potential risk for the environment are listed in Table 2 (Ma et al. 2024).

Table 2 Classification of criteria for the potential environmental risk of heavy metals in soil.

E_r^i	Potential environmental risk index of the elements	RI	Integral potential environmental risk
$E_r^i < 40$	Low	RI < 150	Low
$40 \le E_r^i < 80$	Average	< 300	Average
$80 \le E_r^i < 160$	High	< 600	High
$160 \le E_r^i < 320$	Very high	< 1200	Very high
$E_r^i < 320$	Extra high	RI > 1200	Extra high

Results

Background indicators of heavy metal content in soils

Heavy metal sources are classified as natural or anthropogenic. Geogenic sources include sedimentary rocks, volcanic eruptions, soil formations and rock weathering. Anthropogenic sources, which can cause local and global heavy metal anomalies, include industrial production, agriculture, wastewater and vehicle exhaust. These sources significantly elevate heavy metal concentrations and contribute to ecosystem pollution (Alengebawy et al. 2021).

Therefore, depending on the location of an area studied and its industrial and economic loads, the indicators of heavy metal content outside the immediate impact zone (i.e., at distances greater than 500 m from the bombardment epicenter) differ significantly (Table 3).

Table 3 Total heavy metal content in soil samples taken 500 m from the point of impact (technogenic background, Cf).

Location	Heavy metals, mg/kg of soil						
	Cd	Cr	Pb	Cu	Ni	Mn	Zn
ChD	0.25	16.4	16.5	13.2	8.2	161	38.6
DnD	0.58	45.6	22.4	24.9	29.5	1398	102.5
SmD	0.31	29.6	17.4	16.3	10.3	324.1	51.3
Clarke, Ukraine average (Cgf) [15]	0.17	74.7	17.3	14.5	26.1	628.3	53.0

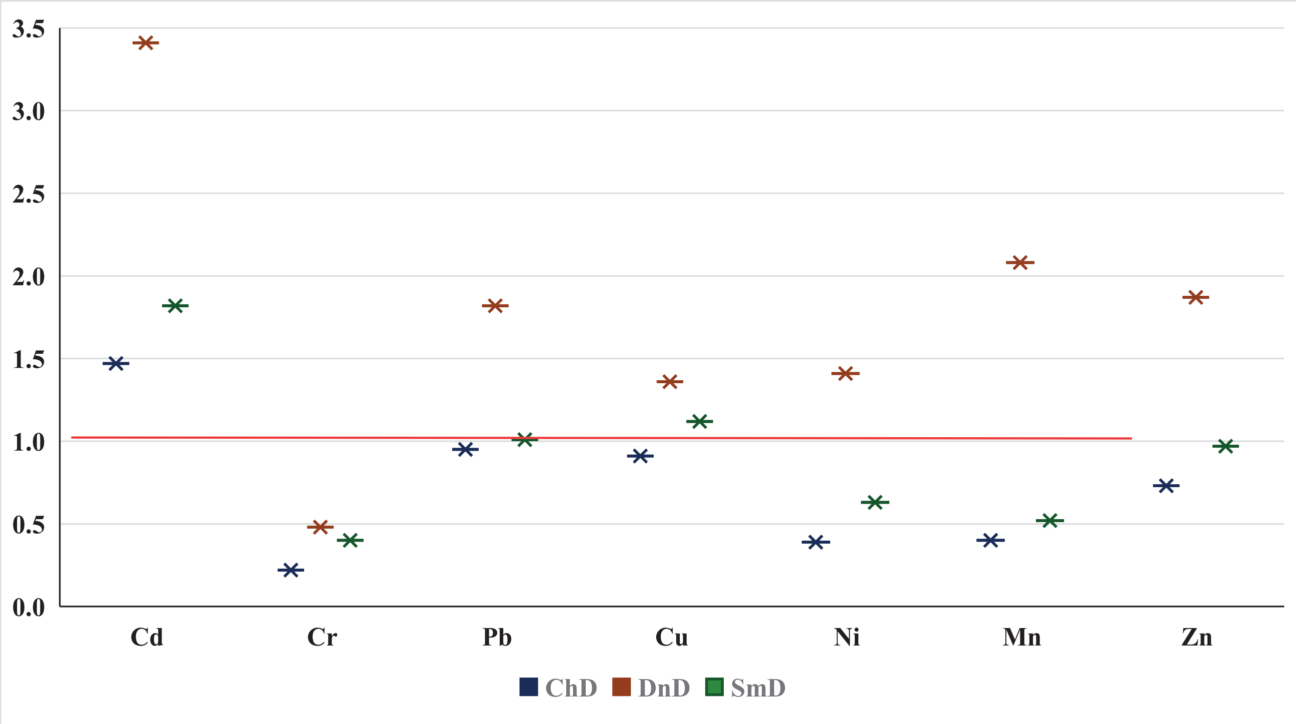

Fig. 3 Extent of the excess (Kt) of heavy metal in soil samples collected 500 m from the point of impact (Cf) relative to the average geochemical background in Ukraine (Cgf). The red line indicates the threshold corresponding to the geological background value (Clarke's average for Ukraine) and marks the limit beyond which the heavy metal concentrations exceeded natural background levels (Cgf).

The lowest accumulation of heavy metals was recorded in soil samples collected from areas furthest from large industrial cities (ChD). In contrast, the highest levels, compared to the average geochemical background in Ukraine, were recorded in soil samples from DnD (Fig. 3).

The technogenic load coefficient (Kt) is an important indicator that reflects the leaching (Kt < 1) or accumulation (Kt > 1) of chemical elements in soil. The heavy metal content in the soil samples from various locations relative to the geochemical background (Cgf) was categorised by their Kt values. At DnD the Kt values for heavy metals exceeded the geochemical background (Clarke's average for Ukraine) for nearly all elements, except chromium, indicating a significant anthropogenic influence in this area. The values for cadmium were 3.4 times higher than the geochemical background, for manganese 2.2 times higher, for copper 1.7 times higher, for nickel 1.1 times higher, for lead 1.3 times higher and for zinc 1.9 times higher than the average geochemical levels. This pattern suggests that heavy metal contamination at DnD is largely due to industrial activities, which are more extensive in this region than in other areas.

Elevated heavy metal concentrations at DnD are largely due to industrialization, with emissions, wastewater discharge and other anthropogenic activities contributing to soil contamination. These processes result in metal concentrations exceeding natural geochemical backgrounds, which indicate the significant effect of human activity. In contrast, at ChD and SmD, cadmium accumulation (Kt 1.5–1.8) and near-threshold levels of copper (Kt 0.91–1.1) and lead (Kt 0.9–1.0) are primarily linked to agriculture, where intensive use of pesticides and fertilizers has led to contamination of both soil and water, potentially exceeding acceptable limits (Defarge et al. 2018; Suciu et al. 2022).

Heavy metal content in soils in the bombardment zone

As noted by Certini et al. (2013), areas of intense military conflict, particularly those marked by the deployment of explosives and munitions, are recognized as significant sources of terrestrial ecosystem contamination during periods of armed conflict. The physical, chemical, and biological properties of soil are compromised by gunfire and explosion. This phenomenon is especially detrimental in agricultural regions, as it negatively affects soil productivity and leads to contamination of the soil-plant-human chain (Lima et al. 2011).

Changes in the chemical composition and content of total heavy metal compounds (Cd, Cr, Pb, Cu, Ni, Mn, Zn) were monitored during military intervention (Ca) in different regions of Ukraine, as summarized in Table 4.

In absolute terms, the soil in the crater at DnD contained higher concentrations of all the monitored elements than that recorded in other regions. However, it should be emphasized that not all exceed the maximum allowable concentration based on background levels (Clarke's average). According to DSTU 4362:2004, Soil Quality. Soil Fertility Indicators," the content of heavy metals should not exceed Clarke's average or 0.5 MPC (maximum permissible concentration).

Table 4 Total content of heavy metal compounds in soil samples from different impact points (Ca).

Location	Heavy metals, mg/kg of soil						
	Cd	Cr	Pb	Cu	Ni	Mn	Zn
ChD	0.98	34.6	64.1	51.9	38.4	887	154.9
DnD	1.68	84.2	123.5	92.5	91.8	2108	226.3
SmD	1.42	59.2	101.6	74.2	59.6	1254	182.3

An analysis of the heavy metals at impacts revealed that the contents of cadmium and chromium at ChD were approximately 0.3 MPC, whereas copper and zinc concentrations were close to background levels, with both at 0.5 MPC. Manganese concentrations were 0.6 MPC, nickel 0.8 MPC, and lead 2.0 MPC (Fig. 4). Cu and Zn are trace elements that do not exceed maximum allowable concentrations. Given the low soil supply of these compounds in the region, no significant exceeding of the acceptable concentrations were detected.

The soil samples from SmD had intermediate levels of contamination in terms of exceeding MPC. The highest excess values were recorded for Pb (3.2 MPC) and Ni (1.2 MPC). The excess of other elements ranges from 0.5 to 0.8 MPC, indicating soil contamination.

The most environmentally concerning situation, in terms of heavy metal content, was recorded at DnD. Here, the excess for lead is 3.2 MPC, nickel 1.8 MPC, manganese 1.4 MPC, with other elements exceeding the background levels by 0.6 to 0.9 MPC. Such high contamination with specific elements is attributed to their accumulation from the explosions of munitions (Zaitsev et al. 2022; Solokha et al. 2023) and the initial technogenic load in the region.

Accumulation of heavy metals as a result of bombardment

Consideration of the aforementioned levels of the technogenic background of heavy metal content (Cf), indicates that military operations and bombardments resulted in a more intense accumulation of certain elements (Table 4). The use of explosive weapons during combat leads to the accumulation of hazardous amounts of lead (1.5–2.9 MPC) and nickel (0.6–1.1 MPC) in the soil (Cw), regardless of the region (Fig. 5). In addition, at SmD and DnD, the excess is 0.6–0.7 MPC for copper, 0.5–0.6 MPC for manganese and 0.5 MPC for chromium at DnD. No exceeding of the maximum permissible concentrations (MPC) was detected at ChD, except for Pb and Ni. The amounts of Cd and Zn in the soils at all the sites did not exceed the MPC values.

The varying degrees of accumulation of these elements may be attributed to both the characteristics of the soil and the processes by which they interact with heavy metals as well as the different sources of their introduction into the soil from military equipment. War-related chemical contamination depends on the intensity and duration of hostilities, the types of weapons used, and the extent of bombardment. The accumulation coefficient of each element relative to the natural or anthropogenic

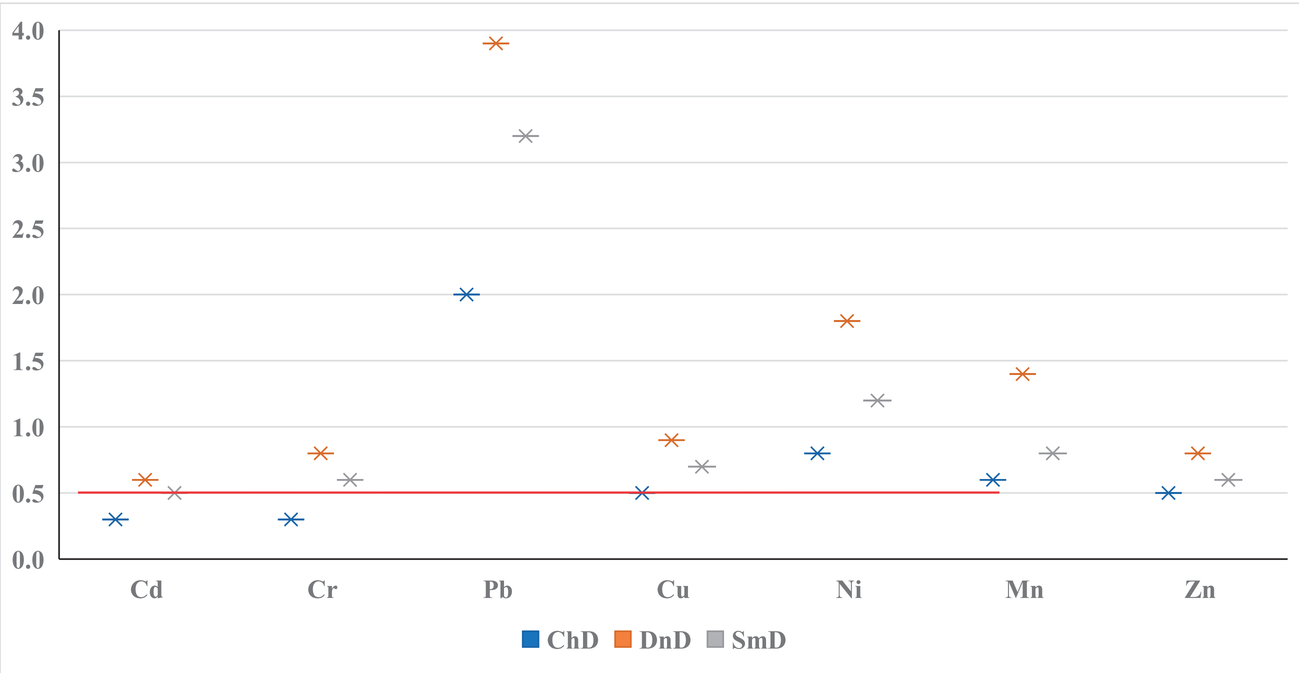

Fig. 4 Extent of the excess of heavy metals in soil samples collected from points of impact (Ca) relative to the corresponding maximum permissible concentrations (MPC). The red line is the threshold of the maximum permissible concentration (MPC).

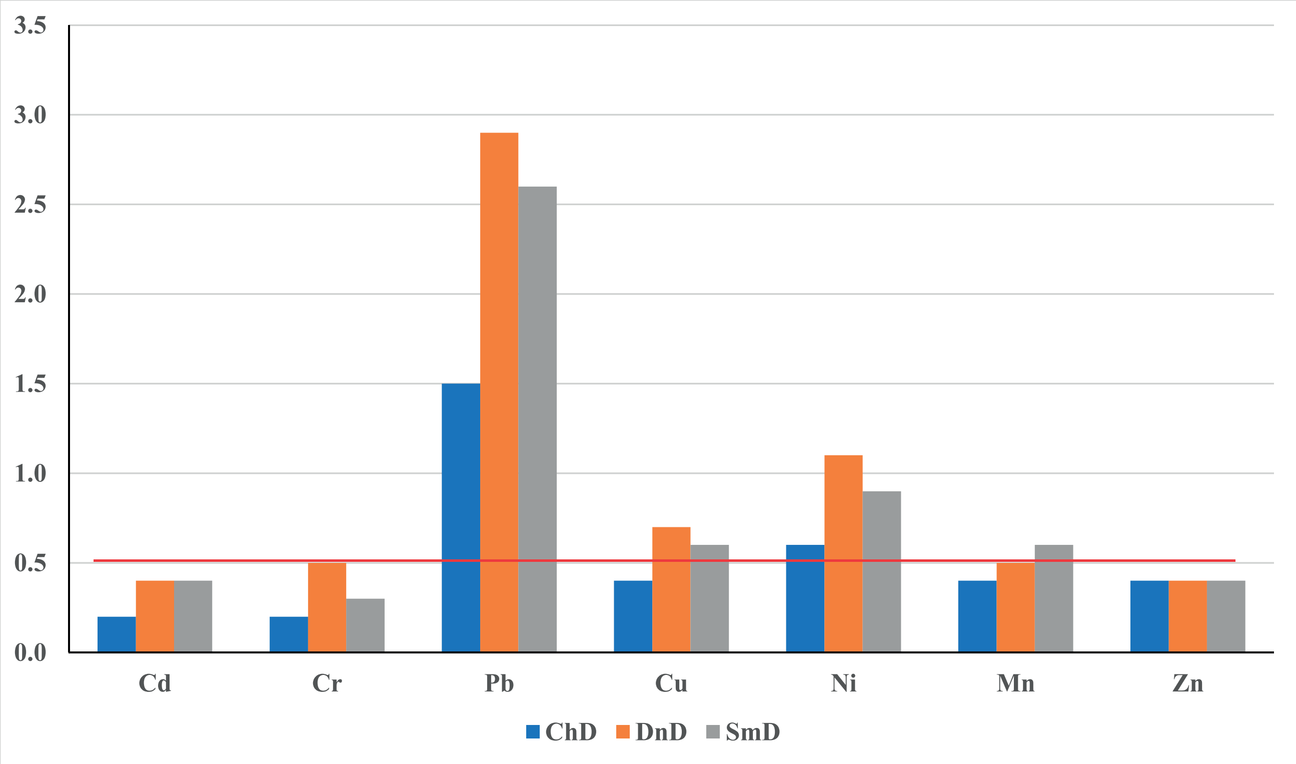

Fig. 5 Extent of the excess of heavy metals in samples collected at points of impact (Ca) relative to the corresponding maximum permissible concentration (MPC) indicators. The red line is the threshold of the acceptable maximum permissible concentration (MPC).

background (Clarke's average) provides a clearer understanding of levels of contamination and shifts in ecological balance (Fig. 6).

The amount of lead resulting from the bombardment was determined to between 2.9–4.8 (Clarke's average). The largest accumulation was recorded at SmD, where the predominant accumulation was for Cd (3.6 Clarke's average) and Mn (2.9 Clarke's average). The

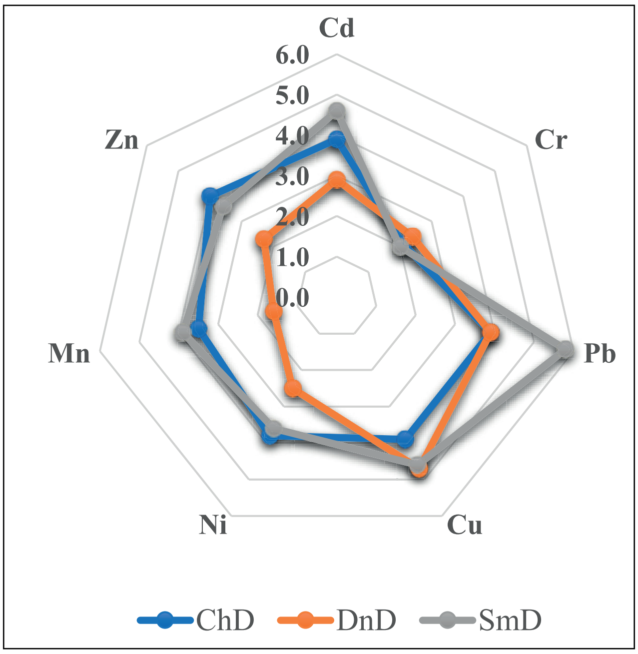

Fig. 6 Coefficient of heavy metal accumulation in soils (Kc) collected from points of impact (Ca) due to bombardment, relative to the anthropogenic background (Cf).

accumulation of Cu at SmD and DnD was almost equal (3.6–3.7 Clarke's average, respectively).

Discussion

Human activity and urbanization have introduced many foreign substances into ecosystems, particularly heavy metals. These elements are strongly absorbed by soil, forming insoluble compounds with phosphates and hydroxides, resulting in their gradual accumulation (Kozlyk et al. 2023). In industrial areas, heavy metals such as Cd, Pb, Cu, Cr, Zn, and Ni often exceed background concentrations. These metals are highly toxic, pose risks for soil, groundwater, and plants, and affect the ecological state of these areas (Kroik 2011; Tarasenko 2013; Chorna et al. 2018).

In the present study, the soil at DnD was distinct from that at the other sites because of its elevated anthropogenic background (Cf). The anthropogenic load coefficient (Kt) for various elements ranged from 0.48 to 3.41, when compared to the average background indicators in Ukraine (Klos et al. 2012). These data indicate that industrial centers are significant sources of heavy metal pollution. Studies by Sutkowska et al. (2020) and others similarly report that heavy metal concentrations in soils in mining areas significantly exceed the geochemical background levels.

Military actions during the full-scale invasion of Ukraine have caused not only the physical degradation of soil but also its chemical contamination. Impacts of shells, burning of military equipment and release of oil destroy ecosystems and contribute to soil and water pollution by heavy metals and toxic elements.

The soil from DnD, which is from outside impact zones, was the most heavily contaminated (Table 3). Relative to the established anthropogenic background (Cf), explosions of shells of various calibres result in the accumulation of heavy metals in soil (Cw), including Pb (2.9 Clarke), Cd (1.9 Clarke), Cr (1.3–1.5 Clarke), Ni (1.3–1.5 Clarke), Zn (1.3–1.5 Clarke), and Mn (0.6 Clarke) – Fig. 5. At locations with the lowest anthropogenic backgrounds, heavy metal accumulation due to bombardment significantly exceeded established background levels (Clarke). For example, the accumulation coefficient for zinc is 3.0 Clarke, for manganese 2.5 Clarke, and for nickel, cadmium, lead 2.8–2.9 Clarke, indicating a deterioration in the environmental as a result of surface craters caused by explosions. Other sources note that the concentrations of metals in the soils of different regions in Ukraine have far exceeded the permissible limits and pose a significant threat to the ecological stability of these ecosystems (Drobitko and Alakbarov 2023). They also report that heavy metals and toxins that accumulate during crop production contribute to contamination (Gamajunova et al. 2021; Sytar and Taran 2022). Large-scale remote sensing data from 2021 and 2022 (Eastern and Southeastern Ukraine) revealed a significant decrease in cultivation in regions with intense fighting (Luhansk and Donetsk) (Solokha et al. 2023). Therefore, the environmental consequences of the war were compounded by an economic crisis. Since the Russian invasion of Ukraine, the price of agricultural products has surpassed that of the food crisis a decade ago (Glauben et al. 2022).

Human exposure to pollutants including heavy metals can have irreversible consequences. The majority of these compounds are resistant to biodegradation or treatment and thus remain in the biosphere for extended periods. They are potentially harmful for both human health and the environment due to their toxicity (Broomandi et al. 2020).

The assessment of heavy metal accumulation resulting solely from bombardment revealed that, based on the degree of heavy metal accumulation (Hakanson 1980; Malovanyy et al. 2024) contamination at ChD can be classified as moderate by all criteria ($1 \leq Kc \leq 3$) whereas at DnD it was moderate for all elements except Cu, for which contamination was considered significant ($3 \leq Kc \leq 6$). At SmD contamination was moderate for Cr, Ni, Mn, and Zn ($1 \leq Kc \leq 3$), and significant for Cd, Pb, and Cu ($3 \leq Kc \leq 6$). Based on Equation 4, the potential environmental risk index of heavy metal accumulation due to bombardment is medium to high (56.9-107.4) for cadmium, and for the other elements it is low (<40).

Because the integral potential environmental risk of heavy metal accumulation does not only consider the heavy metal content in the soil but also the environmental and ecological effects of heavy metals on toxicology, it is important to calculate the RI value (Equation 5) for the total heavy metal content in the soil at the point of impact (Ca) taking into consideration the geochemical background level (Cgf).

Calculations revealed that depending on the general anthropogenic background in the area and the effect of contamination due to bombardment, the degree of potential environmental risk is medium for ChD and high for DnD and SmD (Table 5).

Table 5 The environmental risk index (RI) for heavy metal accumulation in soils at the locations studied.

Location	RI	Level limits	Degree of Integral potential environmental risk
ChD	222	$150 \leq RI < 300$	average
DnD	391	$300 \leq RI < 600$	high
SmD	324		

Conclusions

This study reveals the environmental and health risks of heavy metal contamination in Ukrainian soils due to military activity. Industrial regions like Dnipropetrovsk, are highly contaminated with mainly Pb, Ni and Mn. The environmental risk index (RI) for Dnipropetrovsk and Sumy regions was high (RI 391-324), indicating significant contamination levels, whereas for Chernihiv it was medium (RI 222). This indictes that industrial areas, particularly Dnipropetrovsk, face great risks of heavy metal accumulation being increased by conflict. This research highlights the long-term ecological and health threats posed by metals like Pb, Cd, Ni and Mn, and need for urgent action, including monitoring, soil remediation and public health measures. This study further emphasizes the need to address high contamination levels in regions where it is likely to damage the ecology and prevent further environmental degradation and risk to human health.

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