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Environmental risk assessment of artillery-impacted soils contaminated by heavy metals using pollution indices

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Abstract

Purpose – This proof-of-concept study quantifies environmental and human health risks from heavy metal contamination generated by a single, well-documented artillery strike. Focusing on cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb), we collected paired soil samples from the explosion crater and an unimpacted reference area at a previously pristine site, enabling unambiguous source attribution.
Design/methodology/approach – Samples were digested and analyzed by inductively coupled plasma optical emission spectroscopy and evaluated using a suite of pollution indices (PIs) (Igeo, enrichment factor, contamination factor, Pollution Load Index, Nemerow PI and Cdeg/mCdeg) and ecological risk indices (Eri and Risk Index).
Findings – Compared with reference soils, crater soils showed consistently higher Cd, Cr and Ni; the index ensemble classified the site as mildly to moderately impacted, while integrated ecological risk remained low to moderate. We discuss transport pathways (wind and overland flow) and implications for monitoring and management in conflict-affected landscapes. Because single-strike conditions establish a conservative lower bound for conflict-related contamination, repeated shelling would plausibly increase cumulative burdens and risk.
Originality/value – We outline a longitudinal and spatially replicated follow-up to track attenuation and secondary dispersion and to incorporate biomonitoring endpoints. These findings provide a rigorous baseline for risk communication and for designing targeted mitigation during and after armed conflict.

Keywords War conflicts, Environmental risks, Health risks, Pollution indices, Heavy metals, Artillery
Paper type Research article

1. Introduction

War conflicts have been an integral part of human history, leaving profound marks on societies, economies, and the natural environment (Lawrence *et al*., 2015; Mccally and Leaning, 2000; Singhal, 2019). While the immediate impacts of war are often visible in the form of casualties, destruction of infrastructure, and displacement of populations, the long-term effects on the

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environment and human health are no less significant. Modern warfare, with its reliance on advanced technologies and destructive capabilities, intensifies these consequences, making the study of environmental and health impacts of war an increasingly pressing issue (Adler and Pictures, 2004; Rawtani *et al*., 2022; Sidel and Levy, 2008).

The use of weapons, destruction of infrastructure, and disruption of natural habitats during war contribute to the contamination of air, water, and soil, with pollutants persisting long after hostilities cease. For example, contaminants released into the atmosphere can interact with soil and water systems, creating cascading effects that extend beyond the initial sources (Guidotti *et al*., 2023; Wilby and Hector, 2008; Zalakeviciute *et al*., 2022). These impacts are particularly evident in conflict zones where heavy artillery, bombings, and military vehicles release harmful substances, such as heavy metals, into the environment. This interplay between military activities and environmental degradation underscores the need for a comprehensive understanding of war's long-term consequences. In parallel, the ongoing war in Ukraine has created one of the world's most heavily mine-contaminated landscapes, with authoritative estimates indicating contamination across ∼30% of national territory, a condition that prolongs exposure pathways and complicates recovery (Biswas, 2000; Palczewska, 2015; Schillinger *et al*., 2020; Shumilova *et al*., 2023; Weir *et al*., 2019; Zou *et al*., 2016).

Historical examples further emphasize these risks. For instance, during the Gulf War, the destruction of oil wells in Kuwait released massive amounts of pollutants into the air and soil, with long-lasting ecological and health consequences (Khordagui and Al-Ajmi, 1993; Price, 1998; Samet, 2024; White *et al*., 2016). The Vietnam War also highlights the long-term health and environmental impacts of warfare. During this conflict, the use of herbicides, particularly Agent Orange, led to extensive deforestation, soil degradation, and contamination of water sources with dioxins, causing severe ecological and health consequences for local populations (Frey, 2013; Homer-Dixon, 1991; Korinek *et al*., 2024; Stellman and Stellman, 2018; Sundaram *et al*., 2023).

The health risks associated with war extend beyond direct injuries and fatalities. Particulate matter, volatile organic compounds, and other pollutants released during military operations have been linked to respiratory diseases, cardiovascular problems, and even cancer (Manisalidis *et al*., 2020; Otukoya and Otukoya, 2024; Rengarajan *et al*., 2015; Sacks *et al*., 2011; Wilkinson *et al*., 2012; Zalakeviciute *et al*., 2022). Furthermore, the destruction of water infrastructure often results in the spread of waterborne diseases, exacerbating public health crises in affected regions. The cascading effects of war on health systems, agriculture, and ecosystems create long-term challenges for recovery and sustainability (Amrose *et al*., 2020; Bashir *et al*., 2020; Naik *et al*., 2024; Rengarajan *et al*., 2015; Salman *et al*., 2024; Vyshnevskyi *et al*., 2023).

The issue of decision-making in the use of force remains a critical topic in modern military strategy (Blaha and Brabcová, 2012; Rolenec *et al*., 2021; Nohel *et al*., 2021; Šlouf *et al*., 2023). Countermeasures, such as air defense and artillery protection, reflect the increasing complexity of contemporary warfare (Havlík *et al*., 2024; Hujer *et al*., 2022). The effectiveness of artillery fire, its precision, and the unintended collateral damage are continuously evaluated in relation to achieving military objectives while minimizing economic costs and environmental harm (Havlík *et al*., 2024; Klima *et al*., 2024). However, the absence or failure of automated fire control systems during combat situations often necessitates manual calculations, leading to a higher volume of ammunition fired and, consequently, a greater burden on the environment. This has been recently demonstrated in the ongoing conflict in Ukraine, where manual data processing has contributed to elevated environmental contamination (Šustr *et al*., 2022).

Soil contamination is one of the major environmental impacts of war, and this study documents its prevalence in areas exposed to artillery shelling. Research has shown that explosions release heavy metals and other harmful substances into the soil, disrupting its structure and fertility. Such pollutants can enter the food chain, posing serious risks to human health and biodiversity (Certini *et al*., 2013; Garry and Checchi, 2020; Ismael and Goran, 2024; Pereira *et al*., 2022). Among the most concerning contaminants in conflict-affected areas are cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb), which originate from military waste, explosives, and ammunition residues. These metals pose significant environmental and health risks due to their persistence in soil and toxicity.

Cadmium (Cd) is highly bioaccumulative and linked to kidney damage, bone demineralization, and cancer (Broomandi *et al.*, 2020; Genchi *et al.*, 2020). Chromium (Cr), particularly its hexavalent form (Cr^{6+}), is a potent carcinogen capable of DNA damage and respiratory toxicity (Balali-Mood *et al.*, 2021; Iyaka, 2009). Nickel (Ni) contamination, often linked to metal alloys in munitions, disrupts soil microbiota and exhibits toxic effects on plants and aquatic organisms (Buxton *et al.*, 2019; Genchi *et al.*, 2020a, b). Lead (Pb) is a persistent neurotoxin that accumulates in soils and water, with severe consequences for ecosystems and human health, particularly in children (Balali-Mood *et al.*, 2021; Boskabady *et al.*, 2018; Raj and Das, 2023).

In light of these realities, understanding the environmental and health impacts of war is essential for developing effective mitigation strategies. By addressing the release and movement of pollutants, assessing their effects on biota and ecosystems, and promoting sustainable recovery measures, researchers can contribute to minimizing the long-term consequences of war conflicts. This article aims to provide an overview of the risks associated with war and highlights the urgent need for interdisciplinary research to address this multifaceted issue (Benjamin and Hellerstedt, 2007; Garry and Checchi, 2020; Samet, 2024; Sidel and Levy, 2008; Waqas *et al.*, 2025). Conflicts depress gross domestic product per capita, overburden institutions that monitor emissions and waste management, and shift policy priorities from environmental compliance toward short-term security and reconstruction. This institutional weakening is repeatedly documented in World Bank assessments for fragility, conflict and violence (FCV) contexts and is mirrored in United Nations Environment Programme (UNEP)' scrisis work (Zhang *et al.*, 2025). It follows that coordinated environmental governance—linking security, reconstruction finance, and environmental safeguards—is crucial both during conflict (to prevent deregulation-driven rebounds in pollution) and after (to steer material- and energy-intensive rebuilding onto lower-impact trajectories). The UNEP Conflict and Environment Programme and allied UN initiatives emphasize precisely this integration of diplomacy, monitoring, and restoration, which reduces long-term ecological burdens while supporting the recovery of affected areas.

From available quantitative indicators across conflicts, it is evident that the environmental burden is extensive and measurable: in the case of Ukraine, as of 31 December 2024, estimated recovery needs reached USD 524 billion. The first 24 months of the war generated ≈175 Mt CO_2e (with more recent estimates by the third anniversary rising to ∼230 Mt CO_2e). For comparison, the Khordagui and Al-Ajmi (1993), Price (1998), and White *et al.* (2016) involved >650–750 burning oil wells for ∼9–10 months, with ∼4–6 million barrels/day consumed and ≈3,000–3,400 t/day of soot emissions; in Vietnam (1961–1971), ∼19 million gallons of herbicides were sprayed (including ∼11.2 million gallons of Agent Orange) over ∼3.6–4.5 million acres (≈1.5–1.8 million ha); and in Lebanon, the release of ∼10–15 thousand tonnes of heavy fuel oil (alternatively up to ∼30 thousand tonnes) affected ∼150 km of coastline. In this macro-context of damage, it is particularly relevant that this study employs a matched crater–control design at a previously pristine site, unambiguously attributes the source of contamination to a single strike, and provides a conservative lower bound of metal load quantified by inductively coupled plasma optical emission spectroscopy (ICP-OES) and evaluated by a convergent suite of indices. Such "micro-data" are crucial for scaling risks under repeated shelling, for designing monitoring, and for prioritizing mitigation and decontamination in conflict and post-conflict landscapes (Havlík *et al.*, 2024; Šlouf *et al.*, 2023).

Existing literature on soils in conflict-affected environments approaches the problem predominantly at a macro scale. Authors such as Certini *et al.* (2013) provide a synthetic overview of how military activities comprehensively alter the physical, chemical, and biological properties of soils and, in some cases, act as a significant soil-forming factor. In contrast, Pereira *et al.* (2022) describe the Russian–Ukrainian war at a "total environment" scale, focusing on large-scale emission flows, degradation of ecosystem services, and systemic impacts on climate, water resources, and food security. Other similar studies contribute to understanding the breadth and severity of the environmental impacts of conflicts, but they do not provide a quantitative, causally well-defined estimate of the contribution of a single specific artillery strike to heavy-metal contamination of soil. This pilot study connects to the above literature at a finer, "micro-scale" level and fills precisely this methodological gap. It employs a strictly controlled crater–control design at a previously uncontaminated site, enabling unambiguous attribution of the observed enrichment of Cd, Cr, Ni, and Pb to a single, well-documented shot.

2. Experimental part

Positioning our methodological design. Prior studies show that artillery and training activities elevate heavy metals in soils and sediments and commonly summarize contamination using indices such as Igeo, enrichment factor (EF), contamination factor (CF)/Pollution Load Index (PLI), Nemerow PI and ecological risk (Eri/Risk Index (RI)) (e.g. Certini *et al*., 2013; Pereira *et al*., 2022; Ismael and Goran, 2024). However, most designs are cross-sectional or range-based and cannot cleanly attribute loads to a single, well-documented strike, because legacy inputs and mixed sources confound baselines. We address this gap with a matched crater–control design at a previously pristine site, enabling unambiguous source attribution and providing a conservative lower bound for conflict-related metal burdens. Accordingly, we test:

H1. mean concentrations of Cd, Cr, Ni and Pb are significantly higher in crater soils than in matched reference soils;

H2. A convergent set of pollution and ecological risk indices classifies the study site as mildly to moderately contaminated with low to moderate ecological risk, with these classes being directly interpretable as screening categories in environmental management (no immediate remediation, but a need for enhanced monitoring and targeted risk communication and – under repeated shelling – a potential need for remediation);

H3 (operational). After background normalization, the set of applied indices provides consistent categorization across metrics, which supports its use as a standardized and repeatedly applicable decision-support tool for routine monitoring, site comparison, and prioritization of interventions in conflict and post-conflict landscapes.

Taken together, hypotheses H1–H3 translate our overarching research question on environmental risks in war-affected areas into operational criteria focused on environmental management.

2.1 Sample collection and preparation

Sample collection and preparation were carried out to ensure reliable, reproducible results (University of Defence in collaboration with the Institute of Chemical Processes). To enable clear source attribution and reduce analytical variability, we used a paired crater–control design at a previously pristine site. A single composite crater sample was made from 10 evenly distributed subsamples (≈5 m diameter, ≈20 cm depth). Samples were dried (40 °C), sieved to 0.5 mm, and homogenized; the <0.5 mm fraction was chosen as a pragmatic, conservative compromise to exclude coarse fragments/shrapnel and focus on a finer, more exposure-relevant fraction. Metals were extracted by closed-vessel microwave digestion (aqua regia +0.5 mL hydrofluoric acid (HF)), filtered (0.45 µm), brought to volume, and analyzed in triplicate. Given safety, time, and budget constraints, this streamlined workflow provides reproducible inputs for index-based evaluation and comparison with prior work. Because the study focuses on one well-documented impact site using a composite sample, it should be interpreted as a single-site proof-of-concept providing a conservative lower bound of conflict-related metal inputs rather than a fully generalizable estimate.

Soil samples were collected under strictly controlled conditions from two distinct areas. One area was directly impacted by artillery fire, with the site having never been previously used for any other munitions testing, ensuring that the measured values can be directly attributed to the specific artillery impact, while the other area served as an uncontaminated control zone.

A composite sample was prepared from the crater zone by systematically collecting 10 subsamples from various points within the crater, which measured approximately 5 meters in diameter and 20 centimeters in depth. These subsamples were homogenized to ensure that the composite sample reflected the overall enrichment of contaminants in the impacted area.

A reference sample was simultaneously collected from the control zone to establish baseline concentrations of the monitored elements.

The initial preparation of the collected soil samples involved air-drying at 40 °C to remove moisture. The dried samples were sieved using analytical sieves with a mesh size of 0.5 mm to eliminate coarse particles, such as stones and shrapnel fragments. Representative samples were further processed using a batch mill (IKA®) to reduce particle size and ensure uniformity, enabling precise analytical evaluation.

For chemical analysis, the samples underwent microwave-assisted acid digestion using the Berhhoff Speedwave Xpert system. Each sample, weighing 0.500 g, was digested in a mixture of 10 mL of Aqua Regia and 0.5 mL of HF. The digestion process was conducted in two steps: first, at a temperature of 180 °C and a pressure of 35 bar for 25 min, followed by a second step at 50 °C and 35 bar for 10 min. This program ensured efficient decomposition of the soil matrix and the release of heavy metals into solution. The digested solutions were filtered through nylon syringe filters with a pore size of 0.45 µm and diluted to 50 mL with demineralized water (conductivity <0.1 µS/cm). Each sample was prepared and analyzed in triplicate to ensure repeatability and minimize variability in the results.

The concentrations of cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni) in the digested solutions were determined using ICP-OES (PerkinElmer). The detection limits for the analyzed elements were as follows: 0.01 mg/kg for Cd, 0.05 mg/kg for Pb, 0.02 mg/kg for Cr, and 0.03 mg/kg for Ni. These detection limits enabled precise quantification of trace elements even at low concentrations.

To test differences between crater and control soils, we performed statistical analyses in STATISTICA. Data were checked for normality (Shapiro–Wilk) and homogeneity of variances (Levene) and log10-transformed where needed to meet assumptions ($p > 0.05$). Because the design comprises a single crater–control pair, inference is based on analytical replicates: three independently digested and measured subsamples per group ($n = 3$) were compared using one-way ANOVA with Fisher's least significant difference at $\alpha = 0.05$. For derived indices (Igeo, EF, CF, PLI, Nemerow PI, Cdeg/mCdeg, Eri and RI), uncertainty was propagated across analytical replicates and reported as mean ± SD (shown as error bars). Crater soils were significantly enriched in Cd, Pb, Cr and Ni relative to the control ($p < 0.05$) (Ivan *et al.*, 2025).

2.2 Pollution indices

PIs are essential tools for assessing heavy-metal contamination in soils and its environmental impacts. They quantify contaminant concentrations relative to natural background or regulatory reference levels and support evaluation of potential risks to ecosystems and human health. In this study, these indices are used to determine the extent of soil contamination after artillery impact, clarify the contribution of individual metals, and inform risk management and remediation planning. The following sections summarize the applied indices and their practical interpretation (Tables 1 and 2) (Weissmannová and Pavlovský, 2017).

2.2.1 Single indices of pollution. The Geoaccumulation Index (Igeo) evaluates heavy-metal contamination by comparing current concentrations (Cn) with background/pre-industrial levels (Bn), using a 1.5 correction factor for natural variability to help distinguish anthropogenic from natural contributions (Ji *et al.*, 2013; Lu and Bai, 2010).

Table 1. Classification of single indices: I_{geo}, EF, CF and PI

Index	Formula	Value	Classification
Geoaccumulation Index (I_{geo})	$I_{\mathrm{geo}} = \log_2\left(\frac{C_n}{1{,}5 \cdot B_n}\right)$	$I_{\mathrm{geo}} \leq 0$	Uncontaminated
		$0 < I_{\mathrm{geo}} \leq 1$	Uncontaminated to slightly contaminated
		$2 < I_{\mathrm{geo}} \leq 3$	Moderately to heavily contaminated
		$3 < I_{\mathrm{geo}} \leq 4$	Heavily contaminated
		$4 < I_{\mathrm{geo}} \leq 5$	Heavily to extremely contaminated
		$I_{\mathrm{geo}} > 5$	Extremely heavily contaminated
Enrichment Factor (EF)	$\mathrm{EF} = \frac{\frac{C_n}{C_{Ref}}}{\frac{B_n}{B_{Ref}}}$	$\mathrm{EF} \leq 2$	Very low enrichment
		$2 < \mathrm{EF} < 5$	Moderate enrichment
		$5 < \mathrm{EF} < 20$	Significant enrichment
		$20 < \mathrm{EF} < 40$	Very high enrichment
		$40 \leq \mathrm{EF}$	Extremely high enrichment
Contamination Factor (CF)	$\mathrm{CF} = \frac{C_M}{C_{np}}$	$\mathrm{CF} \leq 1$	Low contamination
		$1 < \mathrm{CF} < 3$	Moderate contamination
		$3 < \mathrm{CF} < 6$	Significant contamination
		$6 \leq \mathrm{CF}$	Very high contamination
Pollution Index (PI)	$\mathrm{PI} = \frac{C_n}{B_n}$	$\mathrm{PI} \leq 1$	Unpolluted to lightly polluted
		$1 < \mathrm{PI} < 3$	Moderately polluted
		$3 \leq \mathrm{PI}$	Heavily polluted

The EF assesses whether elevated metal levels are likely anthropogenic by normalizing the target metal to a conservative reference element (e.g. Al or Fe) and comparing this ratio to baseline values (Abrahim and Parker, 2008; Reimann and De Caritat, 2000; Sutherland, 2000).

The CF is a simple ratio of measured concentration to background (CM/Cnp), indicating the magnitude of contamination at a site (Loska *et al.*, 2004).

The PI compares each metal concentration (Cn) to a predefined reference/limit value (Bn) to screen pollution severity and support prioritization for further investigation or remediation (Weissmannová and Pavlovský, 2017).

2.2.2 Integrated indices and ecological risk indices. The Integrated Pollution Index (IPI) provides a comprehensive measure of overall pollution by averaging PI of multiple contaminants. This index is particularly useful when assessing the cumulative impact of various pollutants in a single area. IPI offers a simplified yet effective approach to understanding the extent of pollution and identifying regions that require immediate attention or remediation efforts (Weissmannová and Chovanec, 2015).

The Nemerow PI (PINemerow) takes a step further by combining the average PI (PIavg) with the maximum observed index (PIMax). This approach provides a more balanced view of contamination by accounting for both typical and peak pollution levels. As a result, PINemerow is highly effective in assessing areas where a few contaminants (n) might pose a disproportionately high risk compared to others (Inengite *et al.*, 2015; Qingjie *et al.*, 2008).

The PLI is a comprehensive measure that combines data on contamination from multiple heavy metals into a single value, providing a cumulative assessment of soil pollution. It is particularly valuable in comparative studies, enabling straightforward benchmarking of pollution levels across various sites or over different time periods. The PLI considers the CF of each individual heavy metal and aggregates these values while accounting for the total number of metals analyzed (n). By offering a simplified yet effective way to evaluate cumulative contamination, the PLI helps identify areas with significant pollution levels that may require targeted intervention or remediation efforts (Liu *et al.*, 2005).

The Degree of Contamination (Cdeg) is a sum of CF for all analyzed pollutants, providing an overall assessment of contamination. This index offers a clear view of the cumulative

Table 2. Classification of integrated indices (IPI, $PI_{Nemerow}$, PLI, C_{deg} and mC_{deg},) and indices of ecological risk (Er^i and RI)

Index	Formula	Value	Classification
Integrated Pollution Index (IPI)	$IPI = mean(PI_i)$	IPI ≤1	Lightly polluted
		1 < IPI <2	Moderately polluted
		2 ≤ IPI	Heavily polluted
Nemerow Pollution Index ($PI_{Nemerow}$)	$PI_{Nemerow} = \sqrt{\frac{PI_{avg}^2 + PI_{Max}^2}{n}}$	$PI_{Nemerow} \leq 0{,}7$	Clean
		$0{,}7 < PI_{Nemerow} < 1$	Warning limit
		$1 < PI_{Nemerow} < 2$	Slightly polluted
		$2 < PI_{Nemerow} > 3$	Moderately polluted
		$3 \leq PI_{Nemerow}$	Heavily polluted
Pollution Load Index (PLI)	$PLI = \sqrt[n]{CF_1 \cdot CF_2 \cdot CF_3 \ldots \cdot CF_n}$	PLI ≤1	Unpolluted
		1 < PLI <2	Unpolluted to slightly polluted
		2 < PLI <3	Slightly polluted
		3 < PLI <4	Slightly to highly polluted
		4 < PLI <5	Highly polluted
		5 ≤ PLI	Very highly polluted
Degree of Contamination (C_{deg})	$C_{deg} = \sum_{i=1}^{n} CF_i$	$C_{deg} \leq 8$	Low degree of contamination
		$8 < C_{deg} < 16$	Moderate degree of contamination
		$16 < C_{deg} < 32$	Considerable degree of contamination
		$32 \leq C_{deg}$	Very high degree of contamination
Modified Degree of Contamination (mC_{deg})	$mC_{deg} = \frac{1}{n} \sum_{i=1}^{n} CF_i$	$mC_{deg} \leq 1{,}5$	Very low degree of contamination
		$1{,}5 < mC_{deg} < 2$	Low degree of contamination
		$2 < mC_{deg} < 4$	Moderate degree of contamination
		$4 < mC_{deg} < 8$	High degree of contamination
		$8 < mC_{deg} < 16$	Very high degree of contamination
		$16 < mC_{deg} < 32$	Extremely high degree of contamination
		$32 \leq mC_{deg}$	Ultra high degree of contamination
Potential Ecological Risk (Er^i)	$E_r^i = T_r^i \cdot C_f^i$	$Er^i \leq 40$	Low ecological risk
		$40 < Er^i < 80$	Moderate ecological risk
		$80 < Er^i < 160$	Considerable ecological risk
		$160 < Er^i < 320$	High ecological risk
		$320 \leq Er^i$	Very high ecological risk
Ecological Risk Index (RI)	$RI = \sum_{i=1}^{n} E_r^i$	RI ≤ 150	Low ecological risk
		150 < RI < 300	Moderate ecological risk
		300 < RI < 600	High ecological risk
		600 ≤ RI	Very high ecological risk

impact of various pollutants in a given area, helping to prioritize locations for remediation based on the total contamination burden (Caeiro *et al.*, 2005).

The Modified Degree of Contamination (mCdeg) adjusts the traditional degree of contamination by normalizing it against the number of analyzed pollutants. This modification enhances the comparability of contamination levels across different studies or regions where the number of investigated pollutants may vary, ensuring a more standardized assessment of pollution (Abrahim and Parker, 2008).

The Potential Ecological Risk (Eri) evaluates the potential ecological hazards posed by individual contaminants by combining their toxicity and contamination levels. It is calculated as the product of the toxic response factor (Tri), which represents the inherent toxicity of the contaminant, and the CF (Cfi), which indicates the extent of its presence compared to natural background levels. This index is crucial for identifying specific pollutants that pose the greatest threats to ecological health, enabling targeted environmental management and remediation efforts (Rahman *et al.*, 2014).

The Ecological RI aggregates the potential ecological risks of all contaminants to provide an overall assessment of the ecological threats in an area. RI is particularly useful in evaluating the cumulative impact of multiple pollutants, offering a clear picture of the ecological risks that could influence local biodiversity and ecosystem stability (Rahman *et al.*, 2014).

2.3 Characteristics of the observed ammunition

The examined 152 mm fragmentation shell OFd is an artillery projectile of Eastern type, widely used in field artillery systems such as howitzers and cannons. This type of ammunition accounts for up to 80% of all artillery shells used in Ukraine, indicating their significance and extensive deployment in the conflict (Ivan *et al.*, 2025).

The fragmentation shell is equipped with an explosive charge composed of a mixture of explosives, typically 2,4,6-trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX), nitroglycerin, and other explosives, which detonate upon impact and disperse a quantity of shrapnel at high speed. This shrapnel causes extensive damage and injuries within several tens of meters from the point of explosion, making the shell effective against infantry and light armored vehicles. The shell casing is made from a durable steel alloy containing additives such as chromium or nickel, which ensures effective fragmentation upon explosion and increases the lethality of the shrapnel (Ivan *et al.*, 2025; Lima *et al.*, 2011).

The designation OFd relates to a specific type or variant of this shell, which may have specific design or functional properties such as a certain weight of explosive charge or a method of activation, determined by the setting of the fuse, which in this case is set for fragmentation effect. These types of shells are often equipped with various types of fuzes that allow for the initiation of the explosion either on impact or at a certain height above the target, enhancing their effectiveness in various combat conditions (Ivan *et al.*, 2025).

3. Results and discussion

3.1 Monitored concentration of selected elements

The graphs (Figure 1) illustrate the concentrations of selected elements in the soil measured before and after the impact of artillery munitions. This visualization allows for a clear comparison of the changes in the concentrations of these elements caused by the impact of the munitions. The black line in each graph represents the preventive value for agricultural soils as established by the current Czech legislation, specifically in *Regulation No. 153/2016. This regulation determines the upper limits of the content of hazardous substances and elements established by implementing legal regulation.*

3.1.1 Cadmium. The concentration of cadmium before the impact of artillery munitions reached a value of 1.19 mg/kg, while after the impact, it increased to 1.36 mg/kg, which corresponds to an increase of 0.17 mg/kg. This rise indicates that both the initial and the newly

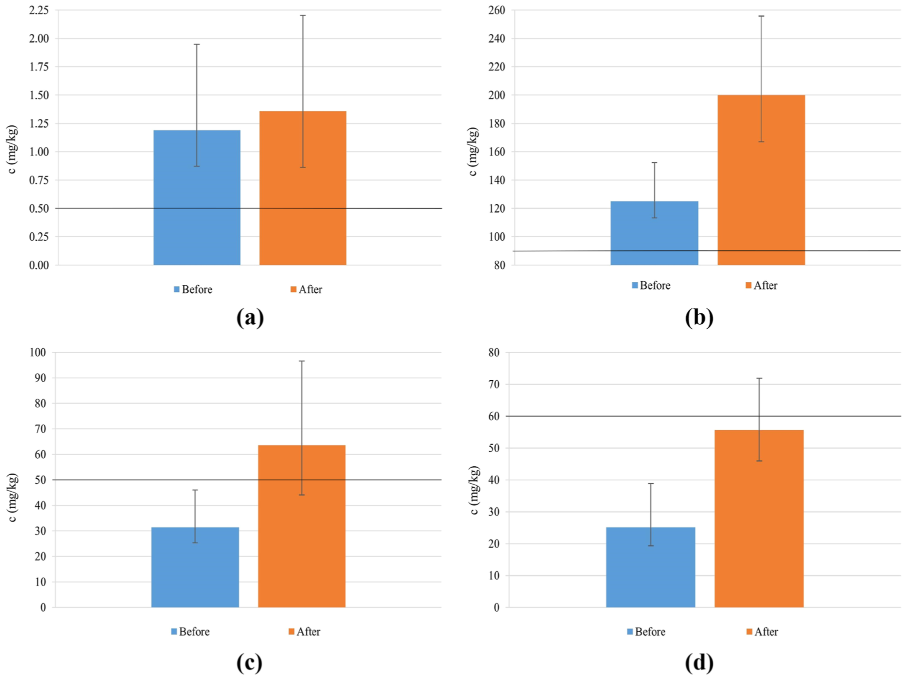


Figure 1. Own elaboration graph comparing concentrations of (a) cadmium, (b) chromium, (c) nickel and (d) lead (mg/kg) in surface soils before (baseline) and after a single, well-documented artillery strike at a previously pristine site. Error bars represent ± standard deviation of analytical triplicates. Asterisks indicate statistically significant differences between before and after

measured concentrations of cadmium significantly exceed the established preventive values (0.50 mg/kg). The higher initial value may reflect a naturally elevated level of cadmium in the area or may be the result of historical contamination associated with military activities (Figure 1).

3.1.2 Chromium. The concentration of chromium in the soil before the impact of artillery munitions was 125 mg/kg, and after the impact, it rose to 200 mg/kg. The observed contribution thus corresponds to an increase of 75 mg/kg. The preventive value for chromium in agricultural soils is set at 90 mg/kg, and both measured values exceed this limit. This excess may again indicate that the higher concentration of chromium in this area may be due to naturally higher values or historical contamination caused by military activities (Figure 1).

3.1.3 Nickel. The original concentration of nickel was 31.4 mg/kg, while after the impact, the value more than doubled to 63.6 mg/kg, indicating an increase of 32.2 mg/kg. Here, it is possible to observe an exceedance of the preventive value (50 mg/kg) after the impact of munitions by 13.6 mg/kg (Figure 1).

3.1.4 Lead. The concentration of lead in the soil increased from an original value of 25.1 mg/kg to 55.6 mg/kg after the impact of artillery munitions, representing a significant increase of 30.5 mg/kg. Although the value after the impact came close to the preventive limit (60 mg/kg), it remains just below this threshold (Figure 1).

3.2 Pollution indices

3.2.1 Geoaccumulation index (I_{geo}). All values of the Geoaccumulation Index for each heavy metal are plotted in the graph below (Figure 2). The I_{geo} value for cadmium (−0.39) indicates

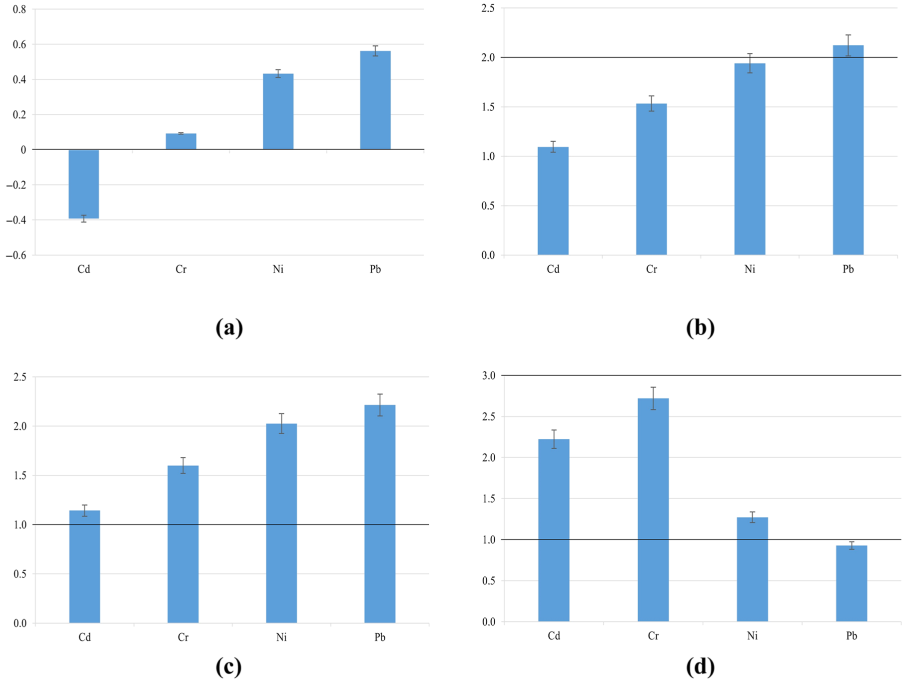


Figure 2. Own elaboration graph comparing single-metric contamination indices for Cd, Cr, Ni and Pb: (a) Geoaccumulation index (Igeo), (b) Enrichment Factor (EF; Al reference), (c) Contamination Factor (CF), (d) Pollution Index (PI; preventive limits as reference). Class thresholds follow Weissmannová and Pavlovský (2017). Error bars represent ± standard deviation of analytical triplicates

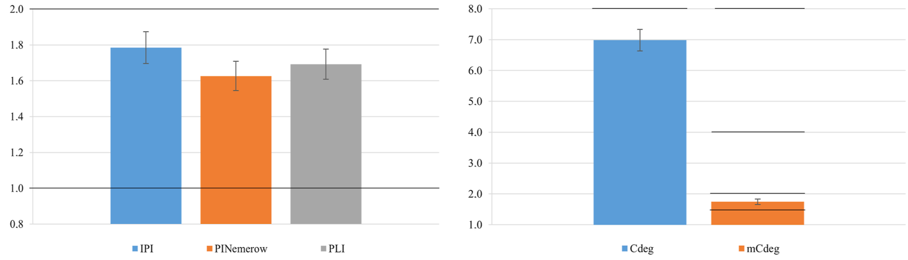
that its level is slightly below the natural geochemical background, indicating an uncontaminated state. The value for chromium (0.09) corresponds to minimal contamination, suggesting a concentration close to the natural background. Nickel (0.43) and lead (0.56) are above natural levels, indicating mild contamination.

3.2.2 Enrichment Factor (EF). Aluminum was chosen as the reference metal for the evaluation. The graph (Figure 2) plots the EF values for cadmium (1.09), chromium (1.53) and nickel (1.94) showing minimal enrichment. In contrast, lead with an EF value of 2.12 already exceeds the moderate enrichment limit.

3.2.3 Contamination factor (CF). The graph (Figure 2) displays the CF values for cadmium (1.14), chromium (1.60), nickel (2.03), and lead (2.22), indicating that all these heavy metals fall into the category of mild contamination.

3.2.4 Pollution index (PI). For calculating the PI, preventive limits for agricultural soils were used as reference values. Below in the graph (Figure 2), values for individual heavy metals are displayed. Cadmium with a value of 2.22 and chromium with a value of 2.72 indicate moderate pollution, signaling that their concentrations are more than double compared to preventive limits and may reflect the influence of military activities. Nickel with a value of 1.27 also shows moderate pollution, while lead with a value of 0.93 indicates only low pollution as its value is lower than the preventive limit.

3.2.5 Integrated Pollution Index (IPI), Nemerow Pollution Index ($PI_{Nemerow}$) and Pollution Load Index (PLI). In the graph (Figure 3), values of three PIs are displayed, reflecting different levels of soil contamination. The IPI has a value of 1.79, placing it in the category of moderate pollution. This index, aggregating average pollution values for all monitored metals, indicates



(a) (b)

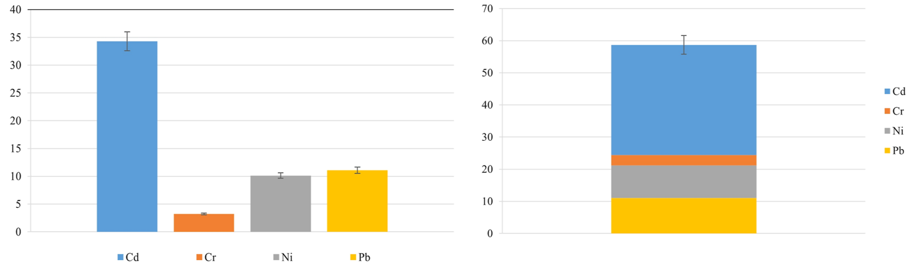
Figure 3. Own elaboration graph comparing integrated contamination metrics: (a) Integrated Pollution Index (IPI), Nemerow Pollution Index (PI_Nemerow), and Pollution Load Index (PLI); (b) Degree of contamination (Cdeg) and modified degree (mCdeg). Class boundaries as specified in Table 2 index definitions after Weissmannová and Pavlovský (2017), Caeiro *et al*. (2005) and Abrahim and Parker (2008). Error bars represent ± standard deviation of analytical triplicates

a significant but not critical level of contamination. The Nemerow PI with a value of 1.63 indicates mild pollution, signaling a lower but still noticeable risk to the environment. The PLI with a value of 1.69 falls into the category of no to mild pollution.

3.2.6 Degree of contamination (C_{deg}) and modified degree of contamination (mC_{deg}). In the graph (Figure 3), values for the degree of contamination (6.98) and modified degree of contamination (1.75) are shown. Both values are classified under the category of low degree of contamination, indicating that although there is a certain level of contamination in the area, it is relatively low and should not pose a significant risk to health or the environment.

3.2.7 Ecological Risk Index. Figure 4 presents the element-specific potential ecological risk (Eri) values for Cd, Cr, Ni, and Pb and their sum expressed as the Ecological RI. The Eri values are 34.29 (Cd), 3.20 (Cr), 10.13 (Ni), and 11.07 (Pb), giving a total RI of 58.69, which indicates low overall ecological risk and suggests that the combined impact of the assessed metals on the ecosystem remains limited. RI is most informative when it includes all relevant metals present at the site, rather than only a narrow selection.

Importantly, the site had not been previously used for munitions testing, so the measured enrichment can be attributed to the studied artillery impact. While a single explosion shows low ecological risk, cumulative effects must be considered: under prolonged or repeated shelling, heavy metals can accumulate and progressively increase contamination and



(a) (b)

Figure 4. Own elaboration graph comparing (a) element-specific potential ecological risk (Er^i) for Cd, Cr, Ni and Pb and (b) aggregate Ecological Risk Index (RI). Toxic-response factors and class boundaries follow Rahman *et al*. (2014). Composite RI value as the sum of individual Eri components; therefore, error bars are displayed only for the constituent Eri values in panel (a) and not for the aggregated RI in panel (b). Error bars represent ± standard deviation of analytical triplicates

ecological risk, underscoring the need for long-term monitoring and ongoing risk assessment in conflict-affected areas.

3.3 Statistical summary and interpretation of uncertainty

For each element, we report the impact effect as a beta coefficient (pre-vs. post-impact) in mg/kg, accompanied by the standard error and the 95% confidence interval (CI) (95% CI) calculated from analytical triplicates (i.e. these reflect measurement/analytical precision rather than field variability of the composite samples). The observed effects are: Cd +0.17 mg/kg (+14%), Cr +75.00 mg/kg (+60%), Ni +32.20 mg/kg (+103%), and Pb +30.5 mg/kg (+122%). Given the nature of the data (composite samples plus technical triplicates), we do not interpret these intervals as environmental replication; this will be addressed in a follow-up longitudinal and spatially replicated study.

3.3.1 Environmental pathways and risks of secondary dispersion. Although this study focused on direct solid-phase enrichment of Cd, Cr, Ni and Pb at the impact site, secondary dispersion processes may increase ecological and health risks beyond the crater. Measured soil conditions (pH 5.8 ± 0.2; electrical conductivity 142 μS/cm) indicate mildly acidic, weakly mineralized soil, which can enhance mobility of divalent cations such as Cd^{2+} and Ni^{2+} by reducing sorption and promoting desorption from clay and oxide surfaces. Under these conditions, Cd is typically the most labile, and small pH decreases or increases in dissolved organic carbon may elevate porewater concentrations and plant-available pools; Ni can behave similarly, particularly when associated with Fe–Mn oxyhydroxides. In contrast, Pb^{2+} generally remains less soluble due to stronger sorption, but it can be efficiently transported bound to fine particles and colloids mobilized by wind erosion and overland flow, consistent with concern about the <2 μm fraction. Total Cr is likely dominated by relatively immobile Cr (III) at pH ≈ 5.8; Cr (VI) is not expected to dominate under the site's slightly acidic, low-oxidant conditions, but because aqua regia digestion does not resolve speciation, Cr-related risk should be interpreted as an upper bound for total chromium rather than Cr (VI). Given the 3–8% clay fraction, contaminants are likely preferentially associated with particles <2 μm, which are susceptible to wind transport (e.g. >5 m/s) and water erosion during heavy rainfall.

While primary contamination appears localized, multi-pathway transport (wind, surface runoff, vertical leaching) may plausibly extend impacts to surrounding ecosystems. Post-conflict evidence supports this: fine particles generated at impact sites (e.g. depleted uranium locations in Iraq, Bosnia and Herzegovina, and Kosovo) can be repeatedly resuspended and transported from hundreds of meters to kilometers, especially where soils are bare or disturbed (Burger, 2012). Similarly, surveys in war-affected Ukraine identify craters and shelling-related hotspots as sources of diffuse contamination via aeolian transport, slope wash and gully erosion (Leal Filho *et al.*, 2024). Together, these observations indicate that localized enrichment can evolve into broader contamination footprints through wind-blown dust, storm runoff and gradual leaching into porewater and shallow groundwater, particularly under mildly acidic, low-buffering conditions.

Beyond geochemistry, biological responses can serve as early warning signals: root elongation in sensitive plants (e.g. *Lactuca sativa*) is inhibited by Cd and Pb at concentrations comparable to those measured here (Di Salvatore *et al.*, 2008), and soil invertebrates (e.g. *Eisenia fetida*) show avoidance responses to metal-contaminated soils, which can be amplified by co-occurring organic pollutants (Gao *et al.*, 2016).

4. Conclusion

This study provides a proof-of-concept assessment of environmental and potential human-health risks from heavy-metal contamination in soils affected by artillery fire. Crater soils showed increased concentrations of Cd, Cr, Ni, and Pb relative to the matched reference, highlighting the direct contribution of a single artillery impact to local soil contamination.

The absence of prior munitions testing at the selected site strengthens internal validity and enables unambiguous attribution of the observed enrichment to the studied strike. Several metals exceeded precautionary limits, underscoring the need for systematic monitoring of impacted areas. The matched crater–control design at a previously pristine site is therefore pivotal, and the convergent suite of contamination and ecological-risk indices (Igeo, EF, CF/PLI, Nemerow PI and Eri/RI) provides cross-validated classification. The resulting effect sizes represent a conservative lower bound for conflict-related metal inputs that can be scaled to multi-strike scenarios (Havlík *et al.*, 2024; Šlouf *et al.*, 2023).

The applied indices classified contamination as mild to moderate; while not immediately critical, potential long-term ecological and health implications cannot be excluded because heavy metals persist and may be redistributed. Importantly, these assessments are based on a single crater and composite surface sampling with analytical (technical) triplicates ($n = 3$ per group); they capture measurement precision rather than field-scale spatial variability. Consequently, the findings should be interpreted as a single-site proof-of-concept rather than a fully generalizable estimate for all artillery-impacted soils. Because substantial concentration changes are expected mainly over longer periods (≥3 months) through desorption, lateral/vertical migration, and biological redistribution, follow-up longitudinal sampling at 3, 6, and 12 months is warranted to track temporal evolution and possible remobilization into other compartments (e.g. groundwater and vegetation).

Under realistic conflict conditions, repeated firing (hundreds to thousands of rounds per day) and fragmentation residues would plausibly increase cumulative burdens, and high-velocity dispersal of fragments and explosive residues may spread metals beyond the crater. Secondary transport via wind, runoff, and leaching can further extend the contamination footprint, meaning the overall impact may be broader than single-crater data suggest. These considerations motivate spatial replication across multiple craters with matched controls and different substrates, together with multi-media sampling (dust, porewater, overland flow, shallow groundwater) and biomonitoring endpoints to link concentration-based metrics to ecological effects.

From a management perspective, the demonstrated multi-index framework is directly usable for routine screening in conflict-affected landscapes and offers a transparent decision aid for triaging sites into enhanced monitoring, targeted risk communication, and—where index classes increase under repeated impacts—active containment or remediation. Among remediation options, functionalized biochar (e.g. Fe–Mn modified) has been shown to reduce Cd^{2+} and Pb^{2+} mobility while improving soil conditions and reducing bioaccumulation (Yang *et al.*, 2024), and broader reviews describe functionalized biochar as a promising, environmentally friendly and potentially cost-effective approach for larger-scale decontamination, while emphasizing the need for optimization and scalable deployment (Lu *et al.*, 2022). Beyond environmental impacts, dual-use applications of military technologies are also being discussed; for example, artillery-based wildfire suppression in inaccessible terrain has been proposed, highlighting potential links between military capabilities and civilian crisis response (Korec *et al.*, 2025).

Taken together, our findings support a tiered management response: sites exceeding precautionary limits but classified as mildly to moderately contaminated should be prioritized for enhanced monitoring, land-use restrictions and targeted risk communication, whereas locations shifting toward higher index classes under repeated shelling may require more intensive interventions such as surface-soil stabilization, partial topsoil removal, or *in situ* immobilization (e.g. functionalized biochar). These index-based tiers can be embedded into post-conflict environmental assessment protocols and the routine monitoring of military training areas, bridging quantitative indicators with operational remediation and surveillance decisions.

References

Abrahim, G.M.S. and Parker, R.J. (2008), “Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from tamaki Estuary, Auckland, New Zealand”, *Environmental Monitoring and Assessment*, Vol. 136 Nos 1-3, pp. 227-238, doi: 10.1007/S10661-007-9678-2/METRICS.

Adler, M. and Pictures, P. (2004), “BattleScars: global conflicts and environmental health”, *Environmental Health Perspectives*, Vol. 112 No. 17, pp. A994-A1003, doi: 10.1289/EHP.112-A994.

Amrose, S.E., Cherukumilli, K. and Wright, N.C. (2020), “Chemical contamination of drinkingwater in resource-constrained settings: global prevalence and piloted mitigation strategies”, *Annual Review of Environment and Resources*, 45, Vol. 45, 2020, pp. 195-226, doi: 10.1146/ANNUREV-ENVIRON-012220-105152/1.

Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M.R. and Sadeghi, M. (2021), “Toxic mechanisms of five heavy metals: Mercury, lead, chromium, cadmium, and arsenic”, *Frontiers in Pharmacology*, Vol. 12, 643972, doi: 10.3389/FPHAR.2021.643972/BIBTEX.

Bashir, I., Lone, F.A., Bhat, R.A., Mir, S.A., Dar, Z.A. and Dar, S.A. (2020), “Concerns and threats of contamination on aquatic ecosystems”, *Bioremediation and Biotechnology: Sustainable Approaches to Pollution Degradation*, pp. 1-26, doi: 10.1007/978-3-030-35691-0_1/TABLES/4.

Benjamin, D. and Hellerstedt, W. (2007), “War and public health”, available at: www.epi.umn.edu/mch, Vol. 73

Biswas, A.K. (2000), “Scientific assessment of the long-term environmental consequences of war”, *The Environmental Consequences of War*, pp. 303-315, doi: 10.1017/CBO9780511522321.017.

Blaha, M. and Brabcová, K. (2012), “Decision-making byEffective C2I system”, *The 7th International Conferenceon Information Warfare and Security*, Seattle (USA), Academic Publishing, pp. 44-51, ISBN: 978-1-908272-29-4. (PDF) Simplification Options for More Efficient Using of Angular and Linear Measuring Rules for Fire Control. available at: https://www.researchgate.net/publication/350026808_Simplification_Options_for_More_Efficient_Using_of_Angular_and_Linear_Measuring_Rules_for_Fire_Control (accessed 2 February 2025).

Boskabady, M., Marefati, N., Farkhondeh, T., Shakeri, F., Farshbaf, A. and Boskabady, M.H. (2018), “The effect of environmental lead exposure on human health and the contribution of inflammatory mechanisms, a review”, *Environment International*, Vol. 120, pp. 404-420, doi: 10.1016/J.ENVINT.2018.08.013.

Broomandi, P., Guney, M., Kim, J.R. and Karaca, F. (2020), “Soil contamination in areas impacted by military activities: a critical review”, *Sustainability*, Vol. 12 No. 21, 9002, doi: 10.3390/SU12219002.

Burger, M. (2012), “The risks of depleted uranium contamination in post-conflict countries: findings and lessons learned from UNEP field assessments”, in Jensen, D. and Lonergan, S. (Eds), *Assessing and Restoring Natural Resources in Post-Conflict Peacebuilding*, Routledge, pp. 163-180, doi: 10.4324/9780203550199-19.

Buxton, S., Garman, E., Heim, K.E., Lyons-Darden, T., Schlekat, C.E., Taylor, M.D. and Oller, A.R. (2019), “Concise review of nickel human health toxicology and ecotoxicology”, *Inorga*, Vol. 7 No. 7, p. 89, doi: 10.3390/INORGANICS7070089.

Caeiro, S., Costa, M.H., Ramos, T.B., Fernandes, F., Silveira, N., Coimbra, A., Medeiros, G. and Painho, M. (2005), “Assessing heavy metal contamination in sado Estuary sediment: an index analysis approach”, *Ecological Indicators*, Vol. 5 No. 2, pp. 151-169, doi: 10.1016/J.ECOLIND.2005.02.001.

Certini, G., Scalenghe, R. and Woods, W.I. (2013), “The impact of warfare on the soil environment”, *Earth-Science Reviews*, Vol. 127, pp. 1-15, doi: 10.1016/J.EARSCIREV.2013.08.009.

Di Salvatore, M., Carafa, A.M. and Carratù, G. (2008), “Assessment of heavy metals phytotoxicity using seed germination and root elongation tests: a comparison of two growth substrates”, *Chemosphere*, Vol. 73 No. 9, pp. 1461-1464, doi: 10.1016/j.chemosphere.2008.07.061.

Frey, R.S. (2013), “Agent Orange and America at war in Vietnam and southeast Asia”, *Human Ecology Review*, Vol. 20 No. 1, pp. 1-10, available at: https://about.jstor.org/terms

Gao, M., Lv, M., Han, M., Song, W. and Wang, D. (2016), “Avoidance behavior of Eisenia fetida in oxytetracycline- and heavy metal-contaminated soils”, *Environmental Toxicology and Pharmacology*, Vol. 47, pp. 119-123, doi: 10.1016/j.etap.2016.09.011.

Garry, S. and Checchi, F. (2020), “Armed conflict and public health: into the 21st century”, *Journal of Public Health*, Vol. 42 No. 3, pp. e287-e298, doi: 10.1093/PUBMED/FDZ095.

Genchi, G., Carocci, A., Lauria, G., Sinicropi, M.S. and Catalano, A. (2020a), “Nickel: human health and environmental toxicology”, *International Journal of Environmental Research and Public Health*, Vol. 17 No. 3, p. 679, doi: 10.3390/IJERPH17030679.

Genchi, G., Sinicropi, M.S., Lauria, G., Carocci, A. and Catalano, A. (2020b), “The effects of cadmium toxicity”, *International Journal of Environmental Research and Public Health*, Vol. 17 No. 11, 3782, doi: 10.3390/IJERPH17113782.

Guidotti, M., Leisewitz, A. and Ranghieri, M.C. (2023), “The endless war: the long-term impact on health and environment of armed conflicts. Annales”, *Proceedings of the Academy of Sciences of Bologna. Class of Physical Sciences*, doi: 10.30682/ANNALESPS2301H.

Havlík, T., Šustr, M., Ivan, J., Pekař, O. and Mušinka, M. (2024), “Evaluation of the effectiveness of a firing battery in self-defense and protection in the area of firing positions using constructive simulation”, *Journal of Defense Modeling and Simulation*. doi: 10.1177/15485129241291579.

Homer-Dixon, T.F. (1991), “On the threshold: environmental changes as causes of acute conflict”, *International Security*, Vol. 16 No. 2, p. 76, doi: 10.2307/2539061.

Hujer, V., Slouf, V. and Farlik, J. (2022), “Utility as a key criterion of a decision-making on structure of the ground based air defence”, *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 13207 LNCS*, pp. 249-260, doi: 10.1007/978-3-030-98260-7_15/FIGURES/6.

Inengite, A.K., Abasi, C.Y. and Walter, C. (2015), “Application of pollution indices for the assessment of heavy metal pollution in flood impacted soil”, *International Research Journal of Pure and Applied Chemistry*, Vol. 8 No. 3, pp. 175-189, doi: 10.9734/IRJPAC/2015/17859.

Ismael, D.S. and Goran, S.M.A. (2024), “Health risk assessment of heavy metals in some vegetables-Erbil city-kurdistan region of Iraq”, *Environmental Monitoring and Assessment*, Vol. 196 No. 5, pp. 1-10, doi: 10.1007/S10661-024-12542-0/TABLES/7.

Ivan, J., Šustr, M., Gregor, J., Potužák, L. and Varecha, J. (2025), “Advancing soil sampling techniques for environmental assessment of artillery impact zones”, *Journal of Ecological Engineering*, Vol. 26 No. 5, pp. 1-14.

Iyaka, Y.A. (2009), “Chromium in soils: a review of its distribution and impacts”, *Continental J. Environmental Sciences*, Vol. 3, pp. 13-18.

Ji, K., Kim, J., Lee, M., Park, S., Kwon, H.J., Cheong, H.K., Jang, J.Y., Kim, D.S., Yu, S., Kim, Y.W., Lee, K.Y., Yang, S.O., Jhung, I.J., Yang, W.H., Paek, D.H., Hong, Y.C. and Choi, K. (2013), “Assessment of exposure to heavy metals and health risks among residents near abandoned metal mines in goseong, Korea”, *Environmental Pollution*, Vol. 178, pp. 322-328, doi: 10.1016/J.ENVPOL.2013.03.031.

Khordagui, H. and Al-Ajmi, D. (1993), “Environmental impact of the gulf war: an integrated preliminary assessment”, *Environmental Management*, Vol. 17 No. 4, pp. 557-562, doi: 10.1007/BF02394670/METRICS.

Klima, M., Bures, M. and Blaha, M. (2024), “Ant colony optimization based algorithm for test path generation problem with negative constraints”, *IEEE International Conference on Software Quality, Reliability and Security, QRS*, pp. 701-712, doi: 10.1109/QRS62785.2024.00075.

Korec, D., Blaha, M., Barta, J. and Varecha, J. (2025), “Innovative approaches to the use of artillery in wildfire suppression”, *Fire*, Vol. 8 No. 6, p. 232, doi: 10.3390/fire8060232.

Korinek, K., Zimmer, Z., Teerawichitchainan, B., Young, Y., Cao Manh, L. and Toan, T.K. (2024), “Cognitive function following early life war-time stress exposure in a cohort of Vietnamese older adults", *Social Science and Medicine*, Vol. 349, 116800, doi: 10.1016/J.SOCSCIMED.2024.116800.

Lawrence, M.J., Stemberger, H.L.J., Zolderdo, A.J., Struthers, D.P. and Cooke, S.J. (2015), "The effects of modern war and military activities on biodiversity and the environment", *Environmental Reviews*, Vol. 23 No. 4, pp. 443-460, doi: 10.1139/ER-2015-0039/ASSET/IMAGES/LARGE/ER-2015-0039F5.JPEG.

Leal Filho, W., Eustachio, J.H.P.P., Fedoruk, M. and Lisovska, T. (2024), "War in Ukraine: an overview of environmental impacts and consequences for human health", *Frontiers in Sustainable Resource Management*, Vol. 3, 1423444, doi: 10.3389/fsrma.2024.1423444.

Lima, D.R.S., Bezerra, M.L.S., Neves, E.B. and Moreira, F.R. (2011), "Impact of ammunition and military explosives on human health and the environment", *Reviews on Environmental Health*, Vol. 26 No. 2, pp. 101-110, doi: 10.1515/REVEH.2011.014/MACHINEREADABLECITATION/RIS.

Liu, W.H., Zhao, J.Z., Ouyang, Z.Y., Söderlund, L. and Liu, G.H. (2005), "Impacts of sewage irrigation on heavy metal distribution and contamination in beijing, China", *Environment International*, Vol. 31 No. 6, pp. 805-812, doi: 10.1016/J.ENVINT.2005.05.042.

Loska, K., Wiechulła, D. and Korus, I. (2004), "Metal contamination of farming soils affected by industry", *Environment International*, Vol. 30 No. 2, pp. 159-165, doi: 10.1016/S0160-4120(03)00157-0.

Lu, S.G. and Bai, S.Q. (2010), "Contamination and potential mobility assessment of heavy metals in urban soils of hangzhou, China: relationship with different land uses", *Environmental Earth Sciences*, Vol. 60 No. 7, pp. 1481-1490, doi: 10.1007/S12665-009-0283-2/TABLES/5.

Lu, Y., Cheng, J., Wang, J., Zhang, F., Tian, Y., Liu, C., Cao, L. and Zhou, Y. (2022), "Efficient remediation of cadmium contamination in soil by functionalized biochar: recent advances, challenges, and future prospects", *Processes*, Vol. 10 No. 8, 1627, doi: 10.3390/pr10081627.

Manisalidis, I., Stavropoulou, E., Stavropoulos, A. and Bezirtzoglou, E. (2020), "Environmental and health impacts of air pollution: a review", *Frontiers in Public Health*, Vol. 8, 505570, doi: 10.3389/FPUBH.2020.00014/BIBTEX.

Mccally, M. and Leaning, J. (2000), "Environment and health: 5. Impact of war", *CMAJ • OCT*, Vol. 163 No. 9, p. 1157.

Naik, S.R., Gamare, D. and Bhopatrao, A. (2024), "Chemical health hazards and toxicity of environmental pollutants on humans, animals and others: an overview", *Journal of Toxicological Studies*, Vol. 2 No. 1, 1135, doi: 10.59400/JTS.V2I1.1135.

Nohel, J., Hradský, Ľ., Flasar, Z., Zahradníček, P. and Křišťálová, D. (2021), "Utilizing the maneuver control system CZ in the course of wargaming modelling and simulation", in Mazal, J., Fagiolini, A., Vasik, P., Turi, M., Bruzzone, A., Pickl, S., Neumann, V. and Stodola, P. (Eds), *Modelling and Simulation for Autonomous Systems (Mesas 2021)*, SPRINGER INTERNATIONAL PUBLISHING, Vol. AG, pp. 357-373, doi: 10.1007/978-3-030-98260-7_23.

Otukoya, T.A. and Otukoya, T.A. (2024), "The scars beyond bullets: recognizing the environmental toll of war", *International Journal of Science and Research Archive*, Vol. 11 No. 1, pp. 1721-1746, doi: 10.30574/IJSRA.2024.11.1.0224.

Palczewska, M. (2015), "Environmental impact of wars and armed conflicts", XXVIII, 2022, doi: 10.2478/kbo-2022-0015, Vol. 281, pp. 100-104.

Pereira, P., Bašić, F., Bogunovic, I. and Barcelo, D. (2022), "Russian-ukrainian war impacts the total environment", *Science of the Total Environment*, Vol. 837, 155865, doi: 10.1016/J.SCITOTENV.2022.155865.

Price, A.R.G. (1998), "Impact of the 1991 gulf war on the coastal environment and ecosystems: current status and future prospects", *Environment International*, Vol. 24 Nos 1-2, pp. 91-96, doi: 10.1016/S0160-4120(97)00124-4.

Qingjie, G., Jun, D., Yunchuan, X., Qingfei, W. and Liqiang, Y. (2008), "Calculating pollution indices by heavy metals in ecological geochemistry assessment and a case study in parks of beijing", *Journal of China University of Geosciences*, Vol. 19 No. 3, pp. 230-241, doi: 10.1016/S1002-0705(08)60042-4.

Rahman, M.S., Saha, N. and Molla, A.H. (2014), “Potential ecological risk assessment of heavy metal contamination in sediment and water body around Dhaka export processing zone, Bangladesh”, *Environmental Earth Sciences*, Vol. 71 No. 5, pp. 2293-2308, doi: 10.1007/S12665-013-2631-5/FIGURES/2.

Raj, K. and Das, A.P. (2023), “Lead pollution: impact on environment and human health and approach for a sustainable solution”, *Environmental Chemistry and Ecotoxicology*, Vol. 5, pp. 79-85, doi: 10.1016/J.ENCECO.2023.02.001.

Rawtani, D., Gupta, G., Khatri, N., Rao, P.K. and Hussain, C.M. (2022), “Environmental damages due to war in Ukraine: a perspective”, *Science of the Total Environment*, Vol. 850, 157932, doi: 10.1016/J.SCITOTENV.2022.157932.

Reimann, C. and De Caritat, P. (2000), “Intrinsic flaws of element enrichment factors (EFs) in environmental geochemistry”, *Environmental Science and Technology*, Vol. 34 No. 24, pp. 5084-5091, doi: 10.1021/ES001339O.

Rengarajan, T., Rajendran, P., Nandakumar, N., Lokeshkumar, B., Rajendran, P. and Nishigaki, I. (2015), “Exposure to polycyclic aromatic hydrocarbons with special focus on cancer”, *Asian Pacific Journal of Tropical Biomedicine*, Vol. 5 No. 3, pp. 182-189, doi: 10.1016/S2221-1691(15)30003-4.

Rolenec, O., Zelený, J., Sedláček, M. and Palasiewicz, T. (2021), in Kolar, P. Ed, “The effect of engineer devices for mobility support used in the NATO on command and control”, *2021 8th International Conference on Military Technologies, ICMT 2021 - Proceedings*, Brno, Institute of Electrical and Electronics Engineers, doi: 10.1109/ICMT52455.2021.9502790.

Sacks, J.D., Stanek, L.W., Luben, T.J., Johns, D.O., Buckley, B.J., Brown, J.S. and Ross, M. (2011), “Particulate matter-induced health effects: who is susceptible?”, *Environmental Health Perspectives*, Vol. 119 No. 4, pp. 446-454, doi: 10.1289/EHP.1002255/SUPPL_FILE/1002255REV_SUPPL.PDF.

Salman, N.A., Al-Mishrey, M.K., Al-Saad, H.T. and Rushdi, A. (2024), “Air pollution in the southern part of Iraq and its health risks”, *Aerosol Optical Depth and Precipitation*, pp. 107-122, doi: 10.1007/978-3-031-55836-8_6.

Samet, J.M. (2024), “War and population health: there is no metric for the horror”, *Population Health Metrics*, Vol. 22 No. 1, pp. 1-2, doi: 10.1186/S12963-023-00321-X/METRICS.

Schillinger, J., Özerol, G., Güven-Griemert, Ş. and Heldeweg, M. (2020), “Water in war: understanding the impacts of armed conflict on water resources and their management”, *Wiley Interdisciplinary Reviews. Water*, Vol. 7 No. 6, e1480, doi: 10.1002/WAT2.1480.

Shumilova, O., Tockner, K., Sukhodolov, A., Khilchevskyi, V., De Meester, L., Stepanenko, S., Trokhymenko, G., Hernández-Agüero, J.A. and Gleick, P. (2023), “Impact of the Russia–Ukraine armed conflict on water resources and water infrastructure”, *Nature Sustainability*, Vol. 6 No. 5, pp. 578-586, doi: 10.1038/s41893-023-01068-x.

Sidel, V.W. and Levy, B.S. (2008), “The health impact of war”, *International Journal of Injury Control and Safety Promotion*, Vol. 15 No. 4, pp. 189-195, doi: 10.1080/17457300802404935.

Singhal, S. (2019), “Early life shocks and mental health: the long-term effect of war in Vietnam”, *Journal of Development Economics*, Vol. 141, 102244, doi: 10.1016/J.JDEVECO.2018.06.002.

Šlouf, V., Blaha, M., Müllner, V., Brizgalová, L. and Pekař, O. (2023), “An alternative model for determining the rational amount of funds allocated to defence of the Czech Republic in conditions of expected risk”, *Obrana a Strategie*, Vol. 2023 No. 1, pp. 149-172, doi: 10.3849/1802-7199.23.2023.01.149-172.

Stellman, J.M. and Stellman, S.D. (2018), “Agent Orange during the Vietnam war: the lingering issue of its civilian and military health impact”, *American Journal of Public Health*, Vol. 108 No. 6, pp. 726-728, doi: 10.2105/AJPH.2018.304426.

Sundaram, M., Filion, A., Akaribo, B.E. and Stephens, P.R. (2023), “Footprint of war: integrating armed conflicts in disease ecology”, *Trends in Parasitology*, Vol. 39 No. 4, pp. 238-241, doi: 10.1016/j.pt.2023.01.007.

Šustr, M., Ivan, J., Blaha, M. and Potužák, L. (2022), “A manual method of artillery fires correction calculation”, *Military Operations Research*, Vol. 27 No. 3, pp. 77-94.

Sutherland, R.A. (2000), “Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii”, *Environmental Geology*, Vol. 39 No. 6, pp. 611-627, doi: 10.1007/S002540050473/METRICS.

Vyshnevskyi, V., Shevchuk, S., Komorin, V., Oleynik, Y. and Gleick, P. (2023), “The destruction of the Kakhovka dam and its consequences”, *Water International*, Vol. 48 No. 5, pp. 631-647, doi: 10.1080/02508060.2023.2247679.

Waqas, M., Farooq, F., Bhat, M.A., Sibt-e-Ali, M. and Batool, K. (2025), “Crafting a sustainable environment through green energy, financial development and agriculture in the BRICS economies”, *Journal of the Knowledge Economy*. doi: 10.1007/s13132-025-02694-w.

Weir, D., McQuillan, D. and Francis, R.A. (2019), “Civilian science: the potential of participatory environmental monitoring in areas affected by armed conflicts”, *Environmental Monitoring and Assessment*, Vol. 191 No. 10, pp. 1-17, doi: 10.1007/S10661-019-7773-9/METRICS.

Weissmannová, D. and Chovanec, P. (2015), “Heavy metal contaminations of urban soils in Ostrava, Czech Republic: assessment of metal pollution and using principal component analysis”, *International Journal of Environmental Research*, Vol. 9 No. 2, pp. 683-696.

Weissmannová, H.D. and Pavlovský, J. (2017), “Indices of soil contamination by heavy metals – methodology of calculation for pollution assessment (minireview)”, *Environmental Monitoring and Assessment*, Vol. 189 No. 12, pp. 1-25, doi: 10.1007/S10661-017-6340-5.

White, R.F., Steele, L., O’Callaghan, J.P., Sullivan, K., Binns, J.H., Golomb, B.A., Bloom, F.E., Bunker, J.A., Crawford, F., Graves, J.C., Hardie, A., Klimas, N., Knox, M., Meggs, W.J., Melling, J., Philbert, M.A. and Grashow, R. (2016), “Recent research on gulf war illness and other health problems in veterans of the 1991 gulf war: effects of toxicant exposures during deployment”, *Cortex*, Vol. 74, pp. 449-475, doi: 10.1016/J.CORTEX.2015.08.022.

Wilby, A. and Hector, A. (2008), “The role of biodiversity”, *Encyclopedia of Life Sciences*. doi: 10.1002/9780470015902.A0021228.

Wilkinson, S., Mills, G., Illidge, R. and Davies, W.J. (2012), “How is ozone pollution reducing our food supply?”, *Journal of Experimental Botany*, Vol. 63 No. 2, pp. 527-536, doi: 10.1093/JXB/ERR317.

Yang, S., Xiao, Q., Li, B., Zhou, T., Cen, Q., Liu, Z. and Zhou, Y. (2024), “Insights into remediation of cadmium and lead contaminated-soil by Fe-Mn modified biochar”, *Journal of Environmental Chemical Engineering*, Vol. 12 No. 3, 112771, doi: 10.1016/j.jece.2024.112771.

Zalakeviciute, R., Mejia, D., Alvarez, H., Bermeo, X., Bonilla-Bedoya, S., Rybarczyk, Y. and Lamb, B. (2022), “War impact on air quality in Ukraine”, *Sustainability*, Vol. 14 No. 21, 13832, doi: 10.3390/SU142113832.

Zhang, X., Bai, X., Guo, L., Waqas, M. and Bhat, M.A. (2025), “How do nuclear energy, geothermal energy, urbanization, and minerals depletion affect environmental quality: new insights from E7 countries”, *Natural Resource Modeling*, Vol. 38 No. 2, e70003, doi: 10.1111/nrm.70003.

Zou, X., Azam, M., Islam, T. and Zaman, K. (2016), “Environment and air pollution like Gun and bullet for low-income countries: war for better health and wealth”, *Environmental Science and Pollution Research*, Vol. 23 No. 4, pp. 3641-3657, doi: 10.1007/S11356-015-5591-3/FIGURES/4.

Further reading

Li, Y., Padoan, E. and Ajmone-Marsan, F. (2021), “Soil particle size fraction and potentially toxic elements bioaccessibility: a review”, *Ecotoxicology and Environmental Safety*, Vol. 209, 111806, doi: 10.1016/j.ecoenv.2020.111806.

Skalny, A.V., Aschner, M., Bobrovnitsky, I.P., Chen, P., Tsatsakis, A., Paoliello, M.M.B., Buha Djordevic, A. and Tinkov, A.A. (2021), “Environmental and health hazards of military metal pollution”, *Environmental Research*, Vol. 201, 111568, doi: 10.1016/J.ENVRES.2021.111568.

Trokhymenko, G., Litvak, S., Litvak, O., Andreeva, A., Rabich, O., Chumak, L., Nalysko, M., Troshyn, M., Komarysta, B. and Sopov, D. (2023), “Assessment of iron and heavy metals accumulation in the soils of the combat zone”, *Eastern-European Journal of Enterprise Technologies*, Vol. 5 10 (125), pp. 6-16, doi: 10.15587/1729-4061.2023.289289.

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