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Military Training Areas as Proxy Sites for Post-Conflict Remediation of Heavy Metals

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Abstract

This study evaluates heavy-metal contamination in soils affected by military activities using training areas as proxies for conflict zones. Soil samples from a shooting range and a grenade range were analyzed using XRF and FAAS after mineralization. High concentrations of Cu, Ni, and Pb were detected, with extreme Pb levels at the shooting range exceeding preventive values. The results support the use of military training sites for developing remediation strategies applicable to war-affected regions. The study provides a relevant proxy-based approach to assess contamination under restricted field conditions and highlights contamination specificity linked to military activities.

KEY WORDS: *copper, lead, military contamination, nickel, soil remediation*

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1. Introduction

Military activities are inherently associated with negative externalities that manifest as degradation and damage to the environment. These impacts may arise from disturbance of the soil cover due to extensive engineering works, which are often accompanied by substantial soil compaction [1], as well as from threats to biodiversity resulting from fires and excessive noise. Another important mechanism is soil acidification caused by explosions, during which nitrates and sulfates are released. Increased acidity subsequently enhances the solubility and bioavailability of heavy metals [1–3]. An integral component of these processes is also the inorganic contamination of soils and waters by heavy metals, which can enter the food chain through contaminated environmental compartments [3].

Heavy-metal contamination in Ukraine resulting from ongoing armed activities constitutes a critical environmental problem with direct impacts on ecosystems [1, 2]. According to [1], the most critical lead (Pb) concentrations in soils were recorded in the Zaporizhzhia region, where exceeded the maximum permissible concentration (MPC) by more than elevenfold. In the Dnipropetrovsk region, measured values exceeded the MPC for Pb by 3.9 times and for nickel (Ni) by 1.8 times. A comparable situation has also been reported for the Mykolaiv, Kharkiv, Sumy, and Chernihiv regions [3, 4]. Given that Ukraine accounts for a substantial share of global grain exports, this contamination may also affect global food security.

Armed conflicts are associated not only with immediate environmental impacts during their duration but also with long-term consequences that may persist for decades after their cessation [1]. Therefore, the identification and evaluation of suitable remediation strategies for inorganic contamination should not be limited to post-conflict periods; rather, these approaches should be considered proactively during ongoing conflicts [1]. Following the cessation of hostilities, the restoration of the civilian economy will be essential. In the Ukraine, where the economy is strongly based on agriculture[1, 3], ensuring the production of safe and uncontaminated food will represent a key priority.

Due to security constraints, direct soil sampling in active combat zones ("hot zones") remains highly restricted [1, 3]. As an alternative, soils from military training areas subjected to long-term military activities can serve as suitable analogues [5, 6]. The aim of this study is to determine the range of heavy-metal contamination in areas affected by military

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activities. Since the primary sources of heavy metals are residues of ammunition and explosives, as well as destroyed military equipment [2, 4], two sites were selected for this purpose: a small-arms shooting range and the impact area of a hand-grenade throwing range.

2. Materials and Methods

To determine the actual level of soil contamination, sampling was conducted at the following locations: a small-arms shooting range (SR) and a hand-grenade throwing range (GR) within the Vyskov Military Training Area, Czech Republic. The sampling conditions are summarized in Table 1. The approximate location of the sampling sites is shown in Figure 1.

Table 1. Sampling conditions.

Parameter	**Shooting range (SR)**	**Grenade range (GR)**
Sampling date	January 31, 2024	November 08, 2024
Environmental conditions	2 °C, cloudy, calm (no wind)	1 °C, cloudy, foggy, NW wind
Type of soil	*Modal Mesobasic Cambisols*	*Modal Mesobasic Cambisols*
Area	2 x 120 m	2 x 12 m
Number of sampling points (subsamples)	28	16
Subsample dry mass	150 g	150 g
Composite sample mass after quartering	1,000 g	600 g

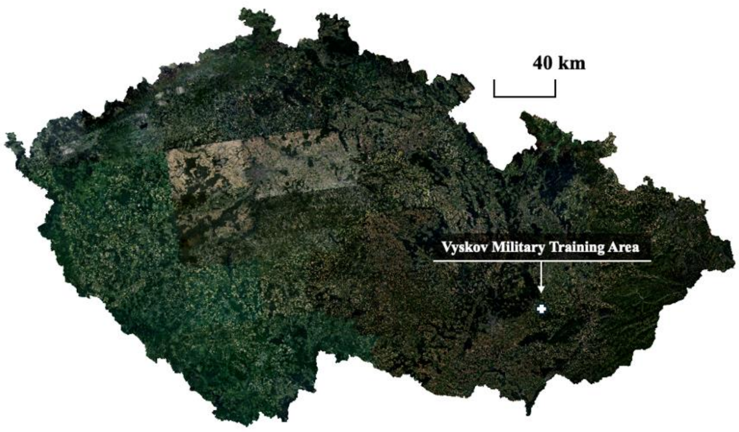

Fig. 1. Geological map of sampling site

Collected soil samples were air-dried, preliminarily disaggregated using a mortar and pestle, sieved through a 1.8 mm mesh, and homogenized by quartering. The resulting composite sample after quartering was subsequently pulverized to analytical fineness using a mortar grinder (RM200, Retsch, Germany). Qualitative screening was performed by X-ray fluorescence spectrometry (XRF) (ElvaX, Elvatech, Ukraine), confirming the presence of Cu, Ni, and Pb in all samples. Sample digestion (mineralization) was carried out according to the HPR-EN-13 by Milestone manufacturer described in [7]. Quantitative determination of selected heavy metals was then performed using flame atomic absorption spectrometry (FAAS) (ContrAA 800D, AnalytikJENA, Germany).

3. Results and Discussion

Qualitative determination of heavy metal content in soils from the SR and GR sites performed using XRF. Representative spectra of heavy metals measured in subsamples SR-I and SR-II, and GR-I and GR-II, are represented in Figure 2a–d. Elevated mass concentrations of Cu, Ni, and Pb were identified across soil samples from both SR and GR sites. However, XRF primarily serves across as a tool for qualitative elemental analysis. Therefore, further analysis was conducted following soil digestion (mineralization) and subsequent quantitative determination using FAAS.

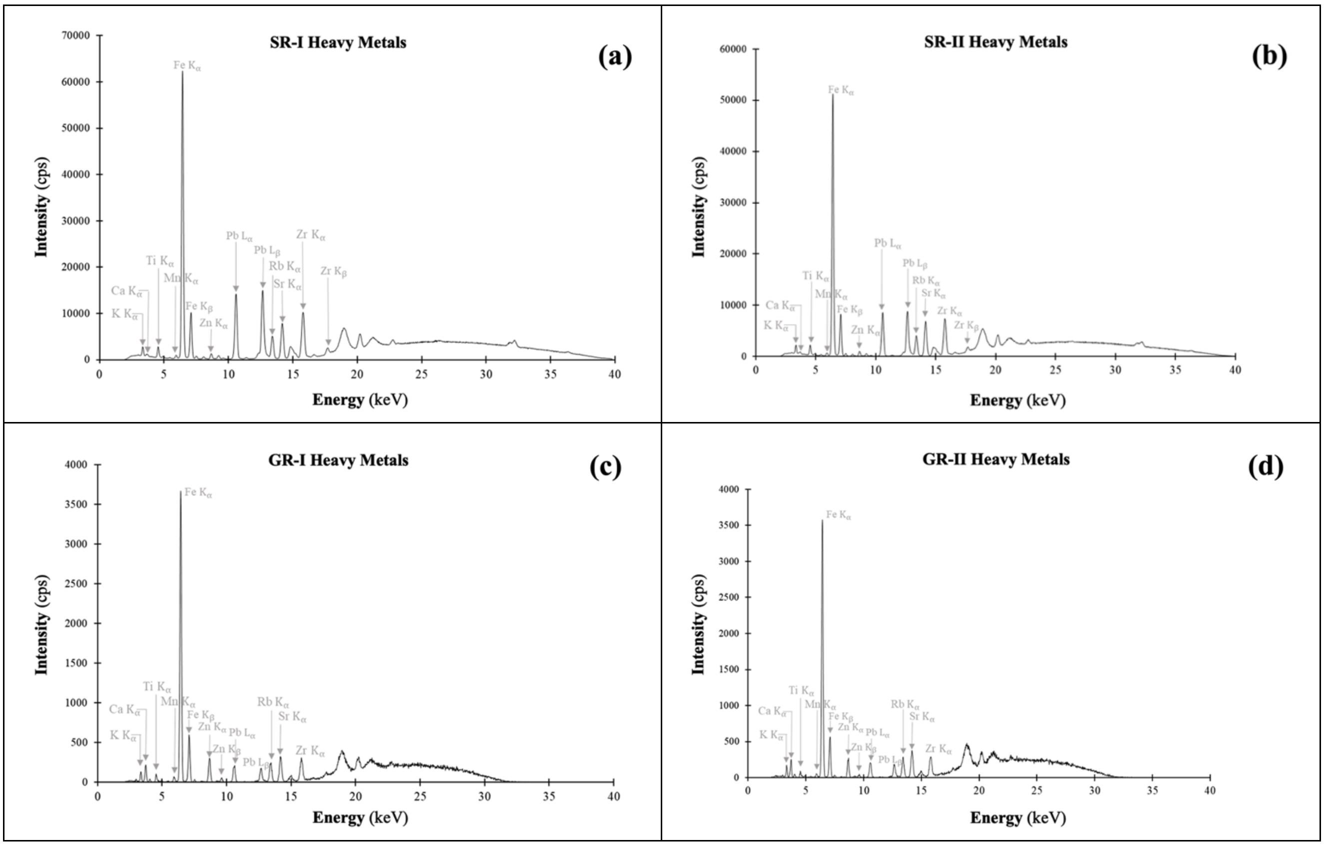

Fig. 2. XRF spectrum.

The concentrations of risk elements determined in soil samples collected from the SR and GR sites are presented in Table 2 and Figure 3. For comparison, the graph also indicates the preventive values for risk-element contents in agricultural soils, determined by aqua regia extraction (mg/kg dry matter), as specified in *Decree No. 153/2016 Coll., on detailed requirements for the protection of agricultural soil quality and amending Decree No. 13/1994 Coll.,* which sets out certain details regarding the protection of the agricultural land fund [8].

Table 2. Mass concentrations of selected metals after mineralization

Soil type	**Cu** (mg/kg)	**Ni** (mg/kg)	**Pb** (mg/kg)
SR	143.87 $\pm$ 2.85	46.53 $\pm$ 1.30	1,380.05 $\pm$ 221.53
GR	110.10 $\pm$ 9.31	44.84 $\pm$0.28	117.78 $\pm$ 3.20

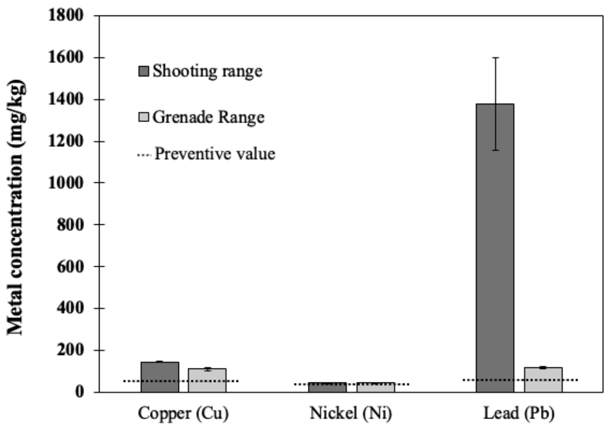

Fig. 3. The determined concentrations of Cu, Ni, and Pb in soil samples.

All measurements were performed in triplicate. Standard deviations are presented in the graphs as error bars. As evident from Figure 3, the measured values exceed the preventive values, with Pb concentrations at the shooting range reaching high levels. Preventive values, as defined by [8], are provided in Table 3.

Table 3. Preventive values [8]

Soil type	**Cu** (mg/kg)	**Ni** (mg/kg)	**Pb** (mg/kg)
Common soils (e.g., sandy loam, loam, clay loam, and clay soils)	60.00	50.00	60.00
Light soils (e.g., sand and gravelly sands)	45.00	45.00	55.00

Given the high concentrations of Pb in SR soils, it should be emphasized that the sampling location at the shooting range corresponded to the bullet impact zone, representing an area with extreme accumulation of Pb. The observed elevated concentrations of Cu, Ni, and Pb are consistent with findings reported in studies [9, 10], demonstrating that the origin of military activities is reflected in the specificity of contamination. Shooting ranges are primarily characterized by Pb and Cu contamination originating from bullets and their jackets. In contrast, heavy metal concentrations in grenade throwing ranges exceed permissible limits but not to a significant extent. This environment is more substantially affected by organic contamination resulting from the use of explosives.

4. Conclusions

The results indicate that both continuous military activities—manifested as sustained soil loading in shooting-range impact zones—and episodic explosive events in areas used for blasting operations and hand-grenade throwing ranges are associated with elevated concentrations of heavy metals. These findings are consistent with the assumption that military training and combat-related activities can represent significant sources of metal inputs to soils, particularly in locations subject to repeated impacts and the accumulation of munition residues.

There is little doubt that large areas of Ukraine affected by the ongoing armed conflict constitute a major environmental challenge that will require systematic remediation efforts once hostilities cease. In this context, soils collected from military training areas can serve as a suitable proxy material for the development and testing of novel, less invasive soil-remediation approaches. Such methods are particularly relevant when the remediation objective is not only to reduce contaminant concentrations, but also to minimize disruption of the soil's biological functions and chemical equilibria.

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