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GIS-based analysis of agrochemical soil conditions and military impact on agricultural lands: A case study of Kherson Oblast

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ABSTRACT

The aim of the study is to determine the impact of military operations on the level of heavy metal contamination in agricultural lands. Specifically, the study intended to establish spatial distribution patterns of their content, compare the obtained indicators with regulatory values, identify areas exceeding maximum allowable concentrations, and assess the possibility of the safe use of such lands for crop production. The object of research is the soil of agricultural lands affected by military operations in the Beryslav and Kherson districts of the Kherson Oblast. In total, 347 soil samples collected from 24 fields with a total area of 1,496.71 hectares were analyzed. The studied fields were subjected to intensive military actions: they were mined, underwent rocket, artillery, and mortar shelling; craters, traces of fires, destroyed equipment, and remains of weapons and ammunition were documented on them. The study was conducted two years after the resumption of active economic land use, which allowed for an assessment of the current state of soil contamination under cultivation conditions and partial restoration of agroecosystems. According to the research results, the most dangerous contamination hotspots were identified: field No. 23 (nickel), fields No. 22, 9, and 7 (manganese), and field No. 10 (lead), where exceedances of regulatory values were recorded. It was found that anthropogenic contamination caused by the consequences of military operations is of a local (mosaic) nature. The results obtained justify the need for detailed contamination mapping and the implementation of differentiated approaches to soil quality management to ensure their environmentally safe use in agricultural production.

Keywords: GIS-based analysis, military impact, agricultural land, agrochemical soil conditions, heavy metals, soil degradation, pollutants, concentration levels.

INTRODUCTION

Monitoring the dynamics of contamination at monitoring sites in the Kherson Oblast is an essential tool for implementing the requirements of the EU Green Deal (European Commission, 2019) regarding comprehensive environmental monitoring. The implementation of state policy in the field of soil monitoring is entrusted to the State Institution «Institute of Soil Protection of Ukraine,» which conducts systematic agrochemical surveys of agricultural lands every five years to track changes in fertility indicators and levels of heavy metal and radionuclide contamination. The obtained data, along with additional monitoring control, serve as a basis for assessing economic damages caused by military operations within national and international legal frameworks (Cabinet of Ministers of Ukraine [CMU], 2022; Ministry of Environmental Protection and Natural Resources of Ukraine, 2022). As a result of ammunition explosions, the burning of military equipment, and infrastructure destruction, the concentrations of toxic elements in the soil (specifically lead, cadmium, zinc, etc.) increase.

Military soil degradation encompasses a complex of chemical, physical, and mechanical disturbances, including crater formation, soil compaction, the removal or mixing of the fertile layer, as well as contamination with explosives, heavy metals, petroleum products, and combustion byproducts. Long-term biogeochemical changes intensify degradation processes and negatively impact the productivity of agroecosystems.

Currently, Ukraine lacks a separate regulatory legal act that comprehensively governs the assessment specifically of military soil degradation. At the same time, its determination is based on existing environmental, land, and sanitary regulations (Verkhovna Rada of Ukraine [VRU], 2001, 2003, 1991), which define general approaches to protection, restoration, and damage compensation. According to DSTU 7874:2015 (2015), a military type of soil degradation caused by armed aggression is distinguished. Degradation is classified by its nature (mechanical, chemical, physical, combined), degree of damage (slight, medium, severe), and the depth of the soil profile disturbance. The assessment of its level is based on the analysis of physical disturbances, chemical contamination (exceeding maximum allowable concentrations), humus loss, and changes in agrochemical indicators. The survey of anthropogenically contaminated lands is regulated by DSTU 7243:2011 (2011), which defines the procedure for sampling, the assessment of the contamination degree, and criteria for the suitability of lands for further use. Resolution (CMU, 2021) establishes maximum allowable concentrations of hazardous substances in soils, serving as the basis for assessing the ecological state of lands.

The chemical component of soil degradation, associated with the accumulation of hazardous substances, is one of the key factors of long-term environmental risk and restrictions on the agricultural use of land. Heavy metal contamination poses the primary danger due to their high toxicity even in minor concentrations (Splodytel et al., 2023; Baliuk et al., 2022).

According to research results (Vidosavljević et al., 2013; Berhe, 2006), military operations in Croatia led to a significant increase in heavy metal concentrations in soils. Specifically, the content of arsenic, mercury, and lead exceeded regulatory values, while nickel concentrations exceeded background levels by 1.03–52.2 times. Importantly, elevated metal levels were recorded even at distances of more than 6 km from active combat zones.

Similar trends were established after the Persian Gulf War, where increased concentrations of cadmium, cobalt, chromium, lead, nickel, titanium, vanadium, and tungsten were recorded (Sadiq et al., 1992). Exceedances of maximum allowable concentrations were also found in the soils of territories subjected to military operations in Bosnia and Herzegovina, Iran, Kuwait, and other regions (Tomic et al., 2018a, 2018b; Broomandi et al., 2017; Denton et al., 2016). The long-term nature of contamination is confirmed by studies that recorded exceedances of allowable heavy metal concentrations on World War I battlefields even 90 years after the conclusion of military operations (Bausinger et al., 2007).

In Ukraine, the negative impact of military operations on soil cover has been recorded since 2014. According to research results (Denisov and Averin, 2017; Kravchenko et al., 2015), exceedances of background heavy metal values by 1.2–12 times were established, particularly regarding mercury, vanadium, and cadmium. The highest concentrations are localized at ammunition explosion sites (Lisova, 2017), confirming the local (mosaic) nature of anthropogenic contamination. Similar results were also obtained by specialists from the State Institution «Institute of Soil Protection of Ukraine» (Zaitsev et al., 2022).

Heavy metals are characterized by high stability in the soil environment; they do not undergo biological decomposition but are only redistributed between ecosystem components. Due to their ability to sorb and form poorly soluble compounds, they accumulate in soils, forming a long-term toxic reservoir of contamination (Korsun et al., 2019; Tkachuk et al., 2020). This creates significant risks to human health, especially in the cases of lead, cadmium, mercury, arsenic, nickel, copper, and zinc (Shepeliuk, 2019; Floria, 2013). They enter the soil environment as a result of ammunition use, destruction of military equipment and infrastructure, and through residues of metal fragments that remain in combat areas for a long time.

Lead belongs to Hazard Class I and is one of the most toxic elements. Cadmium, due to its high mobility, easily accumulates in plants and possesses carcinogenic properties. Other metals (nickel, copper, cobalt, chromium) at elevated concentrations negatively affect biochemical processes in living organisms. Even elements with lower toxicity (manganese, iron) can, in excess, disrupt ecosystem functioning, including the human nervous system (Hupal and Chorniavska, 2018). Generally, the accumulation of heavy metals leads to a decrease in soil fertility, disruption of microbiological activity, and transformation of biogeochemical processes (Shepeliuk, 2019; Pashchenko, 1988).

Thus, monitoring the content of heavy metals in soils is critically important, especially in territories affected by military operations. Systematic surveys allow for the timely identification of contamination hotspots, assessment of the scale of environmental damage, and the making of informed management decisions regarding soil cover restoration. Under the conditions of military impact, such studies are the basis for ensuring safe agricultural production, preserving soil fertility, and maintaining the competitiveness of Ukraine's agricultural sector.

MATERIALS AND METHODS

The research, the results of which are presented in this article, was carried out within the framework of the research project «Study of the Agrochemical State and the Impact of Military Operations on Agricultural Lands to Ensure Sustainable Agro-production» in accordance with Agreement No. DZ/168-2025 dated February 12, 2025, concluded between the State Institution «Institute of Soil Protection of Ukraine» and the Ministry of Education and Science of Ukraine.

Characteristics of the study area and identification of monitoring sites

The Kherson Oblast is located in the southern part of Ukraine, within two natural-agricultural zones: the arid steppe and the dry steppe (Figure 1) (Martyn et al., 2015). The region borders the Mykolaiv, Dnipropetrovsk, and Zaporizhzhia Oblasts, as well as the Crimean Peninsula, and has access to the Black and Azov Seas. The total area of the Oblast is 28.461 thousand km². Administratively, the territory is divided into five districts: Beryslav, Henichesk, Kakhovka, Skadovsk, and Kherson (Verkhovna Rada of Ukraine, 2020).

To assess the ecological and toxicological state of soils on agricultural lands, 347 soil samples were collected from 24 land plots with a total area of 1,496.7111 hectares. The studied plots are located within the Beryslav and Kherson districts of the Kherson Oblast and were directly affected by military operations. The territories were previously mined, subsequently demined, and used in agricultural production for two years prior to the moment of sampling (Figure 2).

The State Institution 'Institute of Soil Protection of Ukraine' conducts surveys of both individual land plots and entire fields exclusively with the consent of landowners or land users. Based on the cadastral numbers of the land plots provided by the land users, 24 experimental fields of agricultural enterprises were formed, the characteristics of which are presented in Table 1.

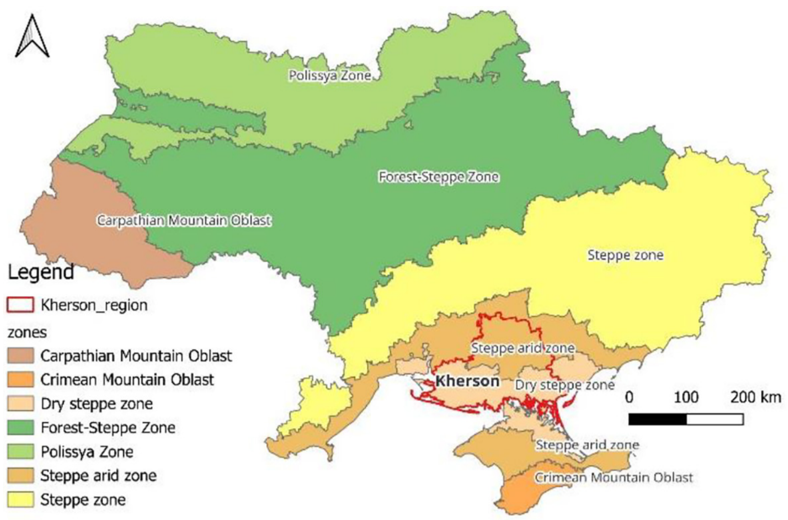

Figure 1. Location and natural-agricultural zoning of Kherson Oblast, CS63

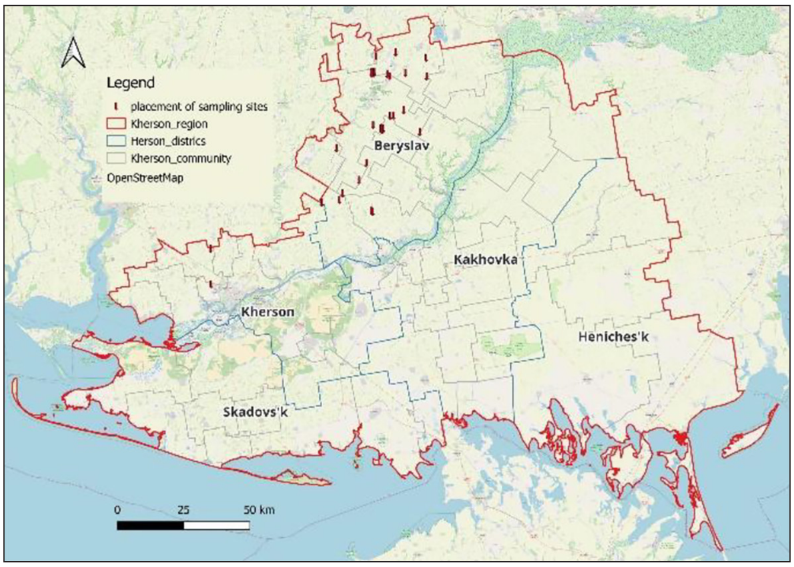

Figure 2. Locations of monitoring sites, Kherson Oblast, CS63

Table 1. Monitoring sites affected by hostilities in the territory of Kherson Oblast

No. field	Area, ha	Location	Number of samples	Agricultural soil groups
Beryslav district				
1	140.5154	Dmytrenka village, Borozenske territorial community	28	**71f**[1]
2	147.7541	Ivanivka village, Vysokopillia territorial community	33	74f
3	146.4508	Novopetrivka village, Vysokopillia territorial community	33	74f
4	143.8000	Blahodatne village, Vysokopillia territorial community	33	74d, 74e, 75e, 76d, 76e, 133e
5	40.1380	Kostyrka village, Vysokopillia territorial community	11	166f
6	29.0396	Nezlamne village, Vysokopillia territorial community	8	**71f**[*], 166f
7	47.6159	Tryfonivka village, Velyka Oleksandrivka territorial community	12	**71f**[*], 166f
8	24.5000	Starosillia village, Velyka Oleksandrivka territorial community	5	74d, 74e, 217
9	75.0774	Velyka Oleksandrivka urban-type settlement	17	**71f**[*], 166f
10	25.6971	Sadok village, Velyka Oleksandrivka territorial community	7	74d, 92b, 133f
11	66.6811	Ishchenka village, Velyka Oleksandrivka territorial community	16	**71f**[*], 166f
12	15.0003	Starytsia village, Borozenske territorial community	3	166f
13	43.3702	Krynychanka village, Velyka Oleksandrivka territorial community	10	**71f**[*]
14	14.6400	Tavriiske village, Tiahynka territorial community	4	**71f**[*]
15	50.0003	Sukhyi Stavok village, Kalynivske territorial community	10	**71f**[*]
16	64.8004	Dmytrenka village, Borozenske territorial community	14	**71f**[*], 166f
17	62.7876	Ivanivka village, Vysokopillia territorial community	14	74f, 77f
18	66.0972	Novopetrivka village, Vysokopillia territorial community	15	74f, 75f
19	88.5453	Blahodatne village, Vysokopillia territorial community	21	**71f**[*], 74f
Kherson district				
20	51.4400	Barvinok village, Chornobaivka territorial community	12	107f, 167f
21	24.5000	Chornobai village, Kherson territorial community	11	110e, 111e
Beryslav district				
22	80.0965	Kamiane village, Velyka Oleksandrivka territorial community	18	**71f**[*], 74f, 75f
23	11.8438	Velyka Oleksandrivka urban-type settlement, Velyka Oleksandrivka territorial community	3	**71f**[*]
24	36.3200	Tarasa Shevchenka village, Beryslav territorial community	9	**71f**[*], 74f

Note: * High-value soils (State Committee of Ukraine, 2003).

Soil cover of monitoring sites and their capacity for heavy metal accumulation

The soil cover of the monitoring sites is represented by the following agro-industrial groups of soils:

71 – Southern chernozems and their slightly and residually saline (solonetzic) varieties;
74 – Southern chernozems, slightly eroded (water-eroded);
75 – Southern chernozems, moderately eroded;
76 – Southern chernozems, severely eroded;
77 – Southern chernozems, slightly deflated (wind-eroded);
92 – Chernozems on sands, non-eroded and slightly eroded;
107 – Dark chestnut slightly saline (solonetzic) soils;
110 – Dark chestnut slightly eroded soils;
111 – Dark chestnut moderately and severely eroded soils;
133 – Meadow soils and their slightly saline and slightly solodized varieties;
166 – Meadow-chernozemic gleyic and gleyic bottom soils;
167 – Meadow-chestnut gleyic and gleyic bottom soils;
217 – Eroded soils and outcrops of eluvium of dense carbonate rocks.

According to their particle size distribution (texture), the soils are classified as: b – clay-sandy; d – light loamy; e – medium loamy; f – heavy loamy and light clayey.

The soil cover of the study area is characterized by significant diversity. Southern chernozems of various erosion degrees and textures predominate, along with dark chestnut, meadow, meadow-chernozemic, and meadow-chestnut soils. Heavy loamy and light clayey chernozems with high potential fertility dominate; however, a portion of them has undergone erosion, accompanied by the degradation of the humus horizon and deterioration of agro-physical properties. Soils with signs of salinity and deflation are common, which reduces their water-physical indicators. In depressed relief elements, meadow and meadow-chernozemic soils with gleying are formed; these are characterized by increased moisture and contribute to the accumulation of pollutants, including heavy metals. Soils of light texture (sandy, loamy-sandy) are noted for their low water-holding capacity and high sensitivity to degradation. Overall, the soil cover is spatially heterogeneous and combines highly fertile but partially degraded chernozems with less productive soils showing signs of erosion, salinity, and gleying. This determines different buffering capacities and specific migration patterns of chemical elements under conditions of additional anthropogenic stress.

The accumulation capacity of soils regarding heavy metals depends on particle size distribution, humus content, and the pH of the environment (Shuman, 1988; Kabata-Pendias, 2010; Alloway, 2013). The highest capacity is characteristic of heavy loamy and humus-rich soils, where metals (Cd, Pb, Cu, Zn) are predominantly fixed in little mobile forms. Conversely, in light-textured soils, migration processes and the risks of groundwater contamination are intensified. In gleyic soils, a periodic increase in metal mobility is possible due to changes in redox conditions.

Thus, in the event of heavy metal input resulting from military operations, their accumulation will prevail in heavy soils, while in light soils, migration and redistribution will dominate, necessitating a differentiated approach to soil quality assessment and management.

Soil sampling

Sampling was carried out within the monitoring sites by dividing the territory into elementary plots of up to 5 hectares, which ensured high spatial detail of contamination. For comparison, during agrochemical certification, the approximate area of such plots is 8–20 hectares (Yatsuk and Baliuk, 2019). Samples were collected in accordance with the requirements of DSTU 4287:2004 (2005) using GPS navigation from a depth of 0–30 cm. On each elementary plot, one composite sample was formed from 20–25 point samples.

The content of mobile forms of heavy metals (Mn, Zn, Cd, Fe, Co, Cu, Ni, Pb) was determined using an ammonium acetate buffer (pH 4.8) according to DSTU 4770.1–7,9:2007 (DSTU 2009a, 2009b, 2009c, 2009d, 2009e, 2008, 2009f, 2009g). This method allows for the assessment of exchangeable and acid-soluble (the most bioavailable) forms of metals.

Unlike international studies that use EDTA, DTPA, or acid digestion (Vidosavljević et al., 2013; Tomic et al., 2018; Denton et al., 2016), the extractant used in this study provides higher values compared to DTPA but lower than those obtained during complete digestion (Kabata-Pendias, 2010; Alloway, 2013). This must be taken into account when comparing results, as differences may be caused by the methodology rather than the level of contamination alone.

The assessment of the ecological and toxicological state was conducted according to the methodology of agrochemical certification (Yatsuk and Baliuk, 2019), taking into account maximum allowable concentrations (CMU, 2022). Statistical processing included the determination of average values, variation indicators, and the coefficient of variation (Tables 2, 3).

Mobile compounds of trace elements, when they exceed certain content standards, act as pollutants. The gradation of the content of trace elements-pollutants is given in Table 2. Manganese, zinc cobalt and copper are extracted by ammonium acetate buffer solution (pH 4.8).

For spatial analysis, a modified integrated pollution index (Z_c) with a threshold filter (Kc > 1), was applied, accounting only for exceedances of background values:

$$Z_c = \sum K_c - (n-1) \quad (1)$$

where: K_c – concentration coefficients of elements exceeding background, n – is the number of such elements.

This approach allows for a more accurate assessment of the impact of military operations.To determine the anthropogenic load (anthropogenically induced deviation from the natural background state), the geoaccumulation index (I_{geo}), was applied, which enables the assessment of the degree of contamination and the identification of local geochemical anomalies (Müller, 1969). The geoaccumulation index (Igeo) is determined by the formula:

$$I_{geo} = log_2 \times \frac{C_n}{(1.5 \times B_n)} \quad (2)$$

where: C_n – is the concentration of the metal, and B_n – is its background value.

The following total concentrations of elements ($mg \cdot kg^{-1}$) were used as background values: Pb – 15.0; Cd – 0.1; Ni – 30.0; Co – 10.0; Zn – 45.0; Cu – 25.0; Mn – 600.0; Fe – 25 000.0.

RESULTS AND DISCUSSION

Specific characteristics of the soil type as a natural buffer for anthropogenic load

Unlike most previous studies conducted in acidic or low-buffer soils (Vidosavljević et al.,

Table 2. Grouping of soils by the content of mobile compounds of trace elements

Groups	Mobile manganese, $mg \cdot kg^{-1}$	Mobile zinc, $mg \cdot kg^{-1}$	Mobile cobalt, $mg \cdot kg^{-1}$	Mobile copper, $mg \cdot kg^{-1}$
Very low	0–5.1	0–1.1	0–0.071	0–0.11
Low	5.1–7.0	1.1–1.5	0.071–0.10	0.11–0.15
Average	7.1–10.0	1.6–2.0	0.11–0.15	0.16–0.20
Elevated	10.1–15.0	2.1–3.0	0.16–0.20	0.21–0.30
High	15.1–20.0	3.1–5.0	0.21–0.30	0.31–0.50
Very high	20.1–49.9	>5.0	0.30–0.49	0.51–0.99

Table 3. Grouping of soils by the content of mobile forms of polluting elements

Groups	Mobile lead, $mg \cdot kg^{-1}$	Mobile zinc, $mg \cdot kg^{-1}$	Mobile cadmium, $mg \cdot kg^{-1}$	Mobile copper, $mg \cdot kg^{-1}$	Mobile nickel, $mg \cdot kg^{-1}$	Mobile cobalt, $mg \cdot kg^{-1}$	Mobile manganese, $mg \cdot kg^{-1}$
Low pollution level	0.8–1.4	5–9	0.10–0.19	1–1.9	2–3	0.5–0.9	50–99
Moderate pollution level	1.5–2.2	10–14	0.20–0.49	2–2.9	4–5	1.0–1.4	100–149
Average pollution level	2.3–3.1	15–19	0.50–0.99	3–3.9	6–7	1.5–1.9	150–199
Elevated pollution level	3.2–3.9	20–24	1.0–1.49	4–4.9	8–9	2.0–2.4	200–249
High pollution level	4–4.9	25–29	1.50–1.99	5–5.9	10–11	2.5–2.9	250–299
Very high pollution level	5	30	2	6	12	3.0	300

2013; Tomic et al., 2018a, 2018b; Sadiq et al., 1992), this work represents the first large-scale agrochemical survey of mobile forms of heavy metals in the chernozems of the Steppe zone of Ukraine. Prior research in Ukraine was primarily local in nature and did not account for the spatial heterogeneity and specific characteristics of chernozems (Kucher and Honcharova, 2021; Yashchenko et al., 2025).

The high cation exchange capacity, significant humus content, and slightly alkaline to alkaline reaction of chernozems determine a different behavior of heavy metals compared to data from international studies. Notably, cadmium and zinc did not show statistically significant accumulation in mobile forms, whereas nickel and manganese form local exceedances of maximum allowable concentrations in zones of point-source anthropogenic stress.

Content of mobile forms of hazard Class I heavy metals

The results obtained confirm that lead (Pb) is a sensitive indicator of anthropogenic, particularly military, stress on the soil cover, which aligns with data regarding its use as a tracer of anthropogenic impact (Broomandi et al., 2017; Alloway, 2013; Kabata-Pendias, 2010). Its accumulation in military-contaminated soils reflects the intensity of ammunition impact and equipment fragmentation, forming a mosaic pattern of contamination.

The established weighted average content of mobile Pb compounds (1.47 mg·kg^{-1}) corresponds to a moderate level of contamination; however, the spatial distribution demonstrates substantial heterogeneity. A low level (0.81–1.44 mg·kg^{-1}) was recorded in most areas, which may indicate partial immobilization of Pb by the soil-absorbing complex. At the same time, local hotspots of medium (2.81 mg·kg^{-1}) and high (5.07 mg·kg^{-1}) contamination were identified in specific plots (No. 4 and No. 10), indicating a point-source nature of pollutant input and possible zones of intense mechanical impact.

The absence of MAC (maximum allowable concentration) exceedances, coupled with the presence of sites with elevated concentrations, underscores the importance of mobile Pb forms as a more sensitive indicator of ecological risk than total content. Significant spatio-temporal variability (CV up to 162.2% at the elementary level) reflects the heterogeneity of the anthropogenic load and the complexity of migration processes within the soil profile.

The weighted average content across the studied plots (fields) varied between 0.49–5.07 mg·kg^{-1}, with a coefficient of variation of 63.8%, indicating a high level of heterogeneity. Within the elementary plots, the variation of the indicator was significantly wider – from 0.01 to 15.0 mg·kg^{-1} of soil, and the coefficient of variation ranged from 6.2% to 162.2%. The highest variability (162.2%, 150.5%, and 113.1%) was recorded within the landholdings of Kostyrka village (plot No. 5), Novopetrivka village (plot No. 3), and Nezlamne village (plot No. 6).

In terms of elementary plots, the content of mobile lead compounds is distributed as follows: 36.85% of the surveyed area is characterized by an absence of contamination, 26.36% by a low level, 17.65% by a moderate level, 9.36% by a medium level, 3.88% by an increased level, 4.37% by a high level, and 1.53% by a very high level of contamination (Figure 3).

The obtained distribution of contamination (with only 36.85% of the area remaining uncontaminated despite the presence of high and very high contamination zones) indicates the formation of local «hotspots» of Pb accumulation, which is characteristic of militarily transformed territories. Such hotspots may have a long-term ecological effect due to the gradual mobilization of the metal following changes in redox conditions or soil acidity.

No exceedances of the MAC for lead were established, which is likely due to the high buffering capacity of chernozems. This capacity is linked to the content of organic matter and clay-humus complexes, which effectively immobilize heavy metals (Kabata-Pendias, 2010; Alloway, 2013). Under these conditions, lead predominantly transforms into immobile forms and is fixed by the soil-absorbing complex, reducing its share in the mobile fraction.

At the same time, even low concentrations of mobile Pb indicate potential bioavailability and long-term ecological risk due to its ability to accumulate in trophic chains (Adriano, 2001; Kabata-Pendias, 2010). Mobile forms of Pb are the most hazardous due to their migration within the soil profile, potential transfer into groundwater, and uptake by plants.

Cadmium (Cd) is a less specific indicator of military impact; however, it often accompanies Pb, Zn, and Cu, forming a typical geochemical

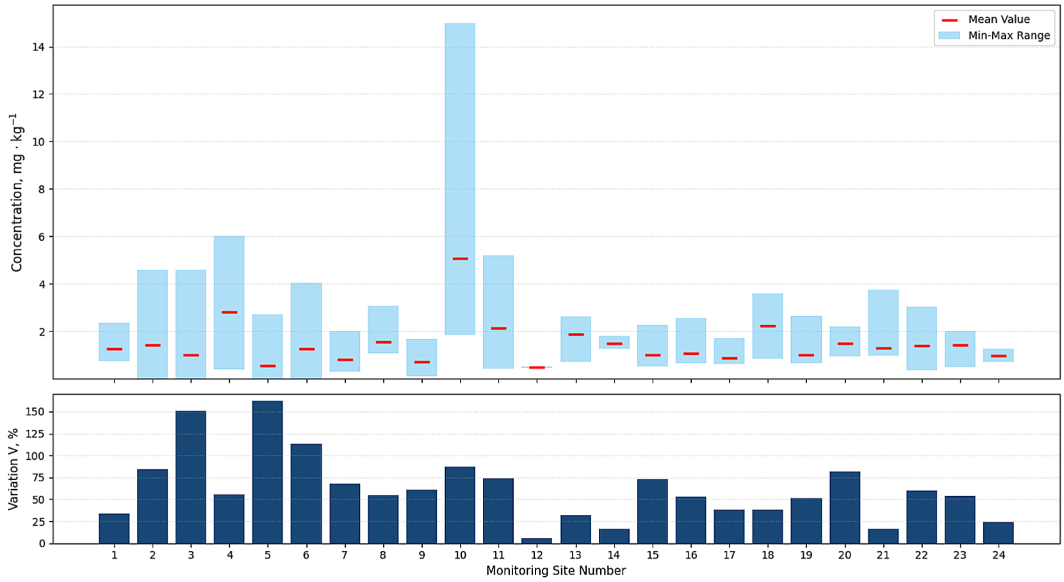

Figure 3. Content of lead mobile compounds

contamination complex (Kicińska and Jelonkiewicz, 2021; Broomandi et al., 2017). It is one of the most mobile and toxic heavy metals, which leads to its active migration into trophic chains; therefore, it is used as a sensitive indicator of ecological risk (Kabata-Pendias, 2011; Alloway, 2013). Unlike lead, which is a more specific marker of ammunition-related load, Cd has a mixed origin (industrial, agrochemical, military), thus its interpretation requires an integrated approach (Adriano, 2001; Kicińska and Jelonkiewicz, 2021).

The weighted average content of mobile cadmium compounds was 0.13 mg·kg^{-1}, which corresponds to a low level of contamination. In most areas (No. 1–9, 14–20, 22, 24), values were within the range of 0.10–0.19 mg·kg^{-1}, while a moderate level was recorded in plot No. 21 (0.29 mg·kg^{-1}). No exceedances of the MAC (0.7 mg·kg^{-1}) were detected. Within individual plots, Cd content varied from 0.05 to 0.29 mg·kg^{-1} (CV = 36.8 %), and at the elementary level – from 0.0 to 0.6 mg·kg^{-1} (CV = 12.3–109.4 %). The highest variability was recorded in Ivanivka village (109.4%) and Dmytrenka village (77.0%). Overall, 36.8% of the area contains no contamination, 31.2% is characterized by a low level, and 31.2% by a moderate level of Cd (Figure 4).

The relatively uniform distribution of Cd is explained by its mobility and dependence on pH and cation exchange capacity. Despite its high toxicity, even low concentrations can pose a risk due to bioaccumulation (Kabata-Pendias A, 2010).

Zinc (Zn) is an essential micronutrient for plants and microorganisms; however, in excess, it exhibits toxicity and suppresses soil biota (Adriano, 2001). It is also considered an indicator of anthropogenic and military impact, though its informativeness increases when combined with other heavy metals. In combat zones, elevated Zn concentrations often accompany Pb, Cu, and Cd, and are associated with equipment corrosion, ammunition fragmentation, and explosive processes (Broomandi et al., 2020; Jiao et al., 2012). Compared to lead, zinc is more mobile in the soil, which results in its higher bioavailability (Alloway, 2013; Kabata-Pendias, 2011).

The weighted average content of mobile zinc compounds in the soils of the studied plots was 0.43 mg·kg^{-1}, which corresponds to a very low supply level; no signs of contamination were established. Within individual fields, the content varied from 0.22 to 1.02 mg·kg^{-1}, with a coefficient of variation of 49.6%, indicating a moderately high level of spatial variability. Within the elementary plots, the variation was significantly wider – ranging from 0.05 to 1.92 mg·kg^{-1} of soil, and the coefficient of variation changed within the range of 15.1–112.0%. The highest variability (112.0%, 57.9%, and 57.0%) was recorded within the landholdings of Kamiane village (plot No. 22), Starosillia village (plot No. 8), and Blahodatne village (plot No. 4).

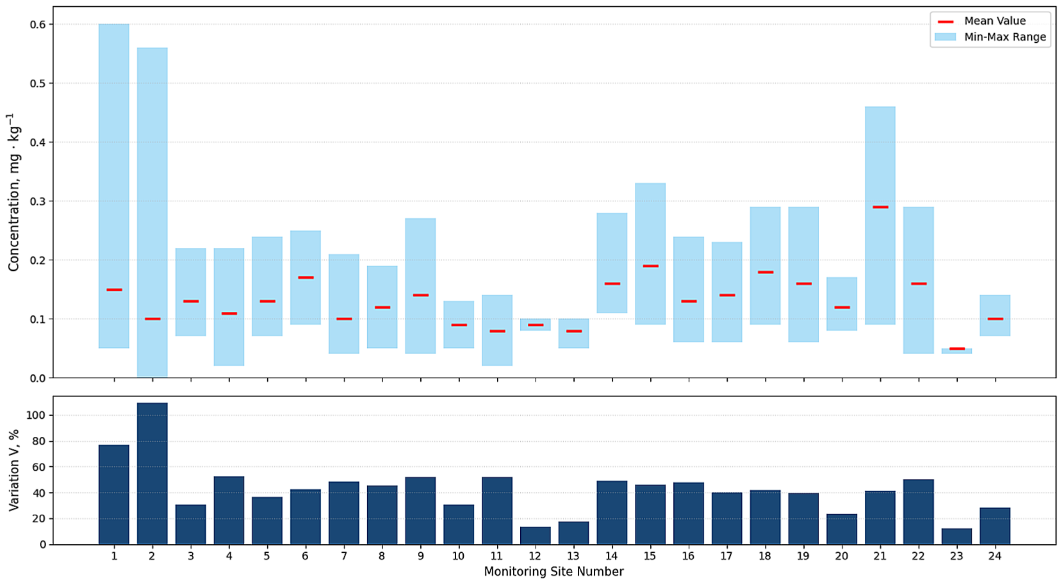

Figure 4. Content of cadmium mobile compounds

In terms of zinc supply levels, the elementary plots are distributed as follows: 96.9% of the surveyed area is characterized by a very low level, 2.5% by a low level, and only 0.6% by a medium level (Figure 5).

Unlike many studies in post-conflict regions, particularly in Croatia and Bosnia and Herzegovina, where increased mobility of Cd and Zn is recorded in acidic and slightly acidic soils, their weighted average content within the monitoring sites of the Kherson Oblast was found to be at background or slightly elevated levels (Vidosavljević et al., 2013; Tomic et al., 2018a). This is due to the specific characteristics of the chernozems in the Steppe zone of Ukraine, which feature an alkaline soil solution reaction (pH 7.5–8.2) and a high content of calcium carbonates. These factors significantly reduce the mobility of Cd^{2+} and Zn^{2+} through their sorption on clay-humus complexes and association with the carbonate fraction (Kabata-Pendias, 2010; Alloway, 2013; Shuman, 1988). Under such conditions, immobile sorbed and carbonate-associated forms prevail, limiting the bioavailability of the elements. An additional factor is the high cation exchange capacity of the heavy loamy chernozems, which ensures the effective retention of Cd^{2+} and Zn^{2+} on humus-mineral complexes and prevents their migration within the soil profile (Shuman, 1988; Kabata-Pendias, 2010). Thus, even with the input of these elements resulting from ammunition detonation, equipment combustion, and the oxidation of metal fragments, the soil acts as an effective geochemical barrier. At the same time, such immobilization is partially reversible: under conditions of acidification, the remobilization of Cd and Zn into more mobile forms is possible (Kabata-Pendias, 2010).

The low supply of mobile zinc, recorded on 96.9% of the area, is a typical agrochemical feature of calcareous steppe soils and is caused by Ca^{2+} antagonism and the strong fixation of Zn within the soil matrix. Further degradation of the humus horizon due to military operations may additionally reduce the soils' capacity to retain bioavailable forms of micronutrients.

Content of mobile forms of hazard Class II heavy metals

Copper (Cu), nickel (Ni), and cobalt (Co) belong to hazard Class II heavy metals. In combat zones, elevated concentrations of Cu and Ni are often associated with the corrosion and destruction of military equipment, explosion byproducts, and the fragmentation of metal structures (Broomandi et al., 2020; Jiao et al., 2012). Cobalt is less frequently considered a direct indicator of ammunition load; however, it can enter the soil along with metal alloys from machinery and as a result of infrastructure destruction.

From a geochemical perspective, Cu, Ni, and Co differ in their mobility in soils: Cu binds strongly to organic matter and clay minerals, whereas Ni and Co are more mobile and can transition into the soil solution upon changes in redox

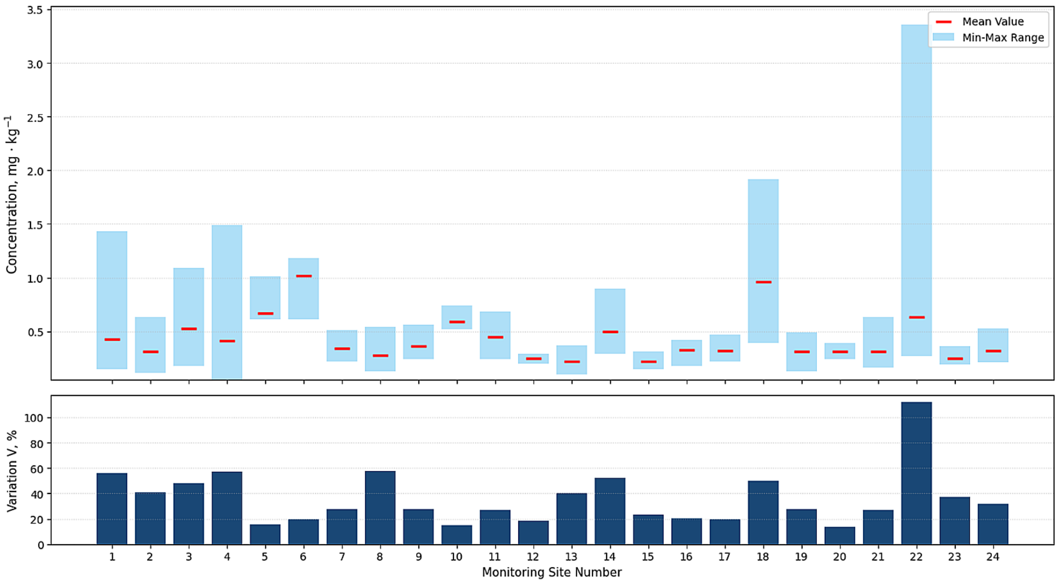

Figure 5. Content of zinc mobile compounds

and acid-base conditions (Alloway, 2013; Kabata-Pendias, 2011).

Overall, these elements are typical components of complex anthropogenic contamination; however, their use as indicators of military impact is correct primarily when combined with other heavy metals (notably Pb, Cd, Zn) and by taking into account the spatial analysis of their distribution (Adriano, 2001).

The weighted average content of mobile copper compounds in the soils of the studied plots was 0.24 mg·kg^{-1}, which corresponds to an increased supply level of this element. Within individual fields, the indicator varied from 0.06 to 0.56 mg·kg^{-1}. The coefficient of variation was 51.2%, indicating a high level of spatial variability. The highest copper values were recorded in plots No. 18 (0.56 mg·kg^{-1}), No. 14, and No. 16 (0.43 mg·kg^{-1} each), located within the landholdings of Tavriiske, Ishchenka, and Starytsia villages.

Within the elementary plots, the variation of the indicator was wider – from 0 to 1.75 mg·kg^{-1} of soil, and the coefficient of variation ranged from 0% to 113.6%. The highest variability (113.6%, 94.5%, and 86.4%) was recorded within the landholdings of Tarasa Shevchenka, Sadok, and Blahodatne villages.

In terms of copper supply levels, the elementary plots are distributed as follows: 42.75% of the surveyed area is characterized by very low and low levels, 9.11% by a low level, 19.6% by an increased level, 17.69% by a high level, and 9.9% by a very high level. At the same time, 0.94% of the area corresponds to a low level of contamination.

Local hotspots of elevated content were recorded in parts of plot No. 18 (1.75 mg·kg^{-1}; area of 5.0044 ha, Tavriiske village) and plot No. 4 (1.0–.19 mg·kg^{-1}; area of 9.091 ha, Blahodatne village) (Figure 6).

According to the research results, no exceedances of the maximum allowable concentration for mobile copper compounds (MAC = 3 mg·kg^{-1}) were established in the soils of the studied plots or elementary plots. Overall, the impact of military operations on the content of mobile copper compounds in the soils of the studied territory is limited and localized, which aligns with literature data (Alloway, 2013).

The research results established that the weighted average content of mobile nickel compounds in the soils of the studied plots was 1.20 mg·kg^{-1}, which corresponds to the background level for this element. Within individual fields, the indicator varied from 0.44 to 3.71 mg·kg^{-1}. The coefficient of variation was 56.32%, indicating a high level of spatial variability. The highest nickel concentrations were recorded in plots No. 23 (3.71 mg·kg^{-1}), No. 9 (1.94 mg·kg^{-1}), and No. 7 (1.75 mg·kg^{-1}), located within the landholdings of the urban-type settlement of Velyka Oleksandrivka and Tryfonivka village.

Within the elementary plots, the variation of the indicator was wider – from 0.11 to 7.82 mg·kg^{-1} of soil, and the coefficient of variation

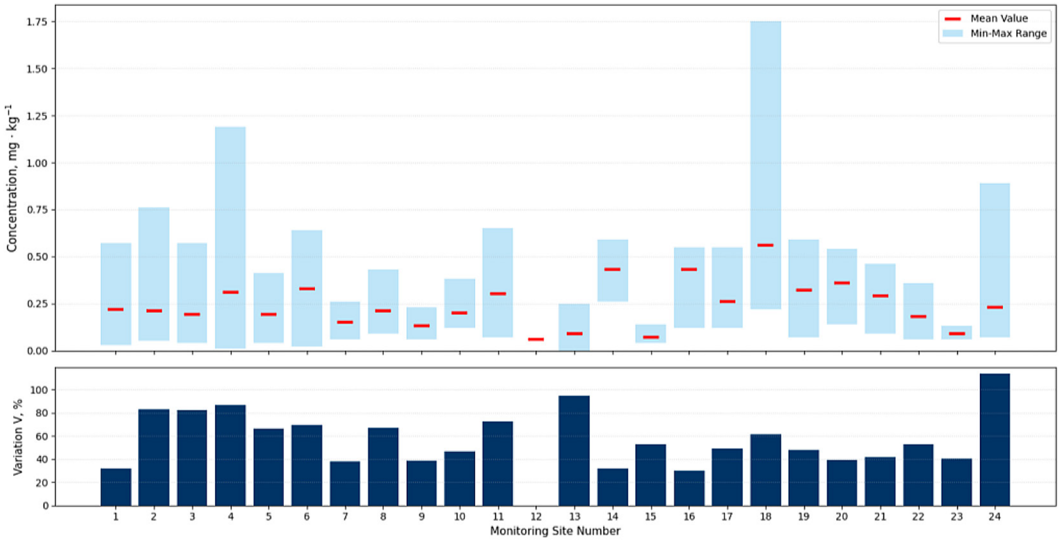

Figure 6. Content of copper mobile compounds

changed within the range of 2.9–91.9%. The highest variability (91.9%, 56.8%, and 49.2%) was recorded within the landholdings of Velyka Oleksandrivka, Tavriiske village, and Nezlamne village.

In terms of elementary plots, the content of mobile nickel compounds is distributed as follows: 94.61% of the surveyed area is characterized by an absence of contamination, 5.15% by a low level, and only 0.24% by an increased level. Low-level contamination was established in plots No. 2 (2.15–2.93 mg·kg^{-1}, area of 19.91 ha, Ivanivka village), No. 3 (2.12–2.46 mg·kg^{-1}, area of 12.03 ha, Novopetrivka village), No. 6 (2.74 mg·kg^{-1}, area of 3.98 ha, Nezlamne village), No. 7 (2.28 mg·kg^{-1}, area of 4.56 ha, Tryfonivka village), No. 9 (2.01–2.58 mg·kg^{-1}, area of 27.57 ha, Tryfonivka village), and No. 22 (2.17 mg·kg^{-1}, area of 3.83 ha, Kamiane village). At the same time, in plot No. 23 (Velyka Oleksandrivka), both a low level of contamination (2.07 mg·kg^{-1}, area of 5.1 ha) and an increased level (7.82 mg·kg^{-1}, area of 3.55 ha) were detected; the latter exceeds the maximum allowable concentration (MAC = 4 mg·kg^{-1}) by 1.96 times (Figure 7).

At the same time, the soil cover of the monitoring plots in the Kherson Oblast is primarily represented by chernozems, which are characterized by high buffering capacity, significant humus content, and high cation exchange capacity. This facilitates the fixation of heavy metals and reduces their migration and bioavailability (Kabata-Pendias, 2011; Alloway, 2013).

The analyses were conducted after the conclusion of the active phase of military operations and the partial resumption of agricultural production, including mechanical soil tillage for at least two growing seasons. The mixing of the soil mass could have facilitated the dispersion of pollutants and reduced the contrast of local anomalies (McLaughlin et al., 2011). Furthermore, the use of various types of ammunition with different intensities should be considered, as this leads to variability in the composition and volume of metal input into the soil.

The localized nature of contamination and relatively moderate exceedances of heavy metal concentrations were also demonstrated in a study by Tomic et al. (2018) for the territories of Bosnia and Herzegovina, where nickel was characterized by significant spatial variability without the formation of continuous zones of high contamination. This confirms that in post-conflict agrolandscapes, the level and scale of contamination are determined not only by the fact of military impact but also by soil properties, the duration of post-war recovery, and the nature of the anthropogenic load.

Taking into account the specific characteristics of the territories affected by military operations, the elevated nickel content may be associated with the input of destruction products from metal structures, ammunition fragments, or military equipment. This aligns with the results of studies in conflict zones where the sources of Ni are metal fragments and combustion products (Broomandi et al.; Sadiq et al.).

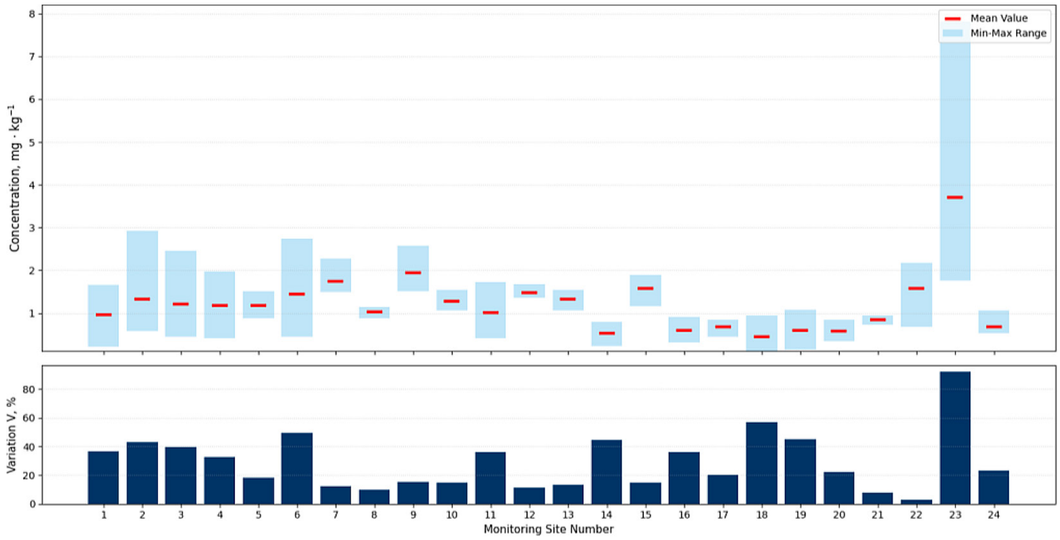

Figure 7. Content of nickel mobile compounds

The weighted average content of mobile cobalt compounds in the soils of the studied plots was 0.41 mg·kg^{-1}, which corresponds to the background level for this element. Within individual fields, the indicator varied from 0.06 to 0.78 mg·kg^{-1}. The coefficient of variation was 48.4%, indicating a high level of variability and significant spatial heterogeneity in the distribution of cobalt. The highest cobalt concentrations were recorded in plots No. 12 (0.78 mg·kg^{-1}), No. 9 (0.73 mg·kg^{-1}), No. 21 (0.65 mg·kg^{-1}), and No. 16 (0.64 mg·kg^{-1}), located within the landholdings of Velyka Oleksandrivka, Tryfonivka, Chornobaivka, and Starytsia.

Within the elementary plots, the variation of the indicator was wider – from 0.0 to 2.11 mg·kg^{-1} of soil, and the coefficient of variation ranged from 12.2% to 163.8%. The highest variability (163.8%, 106.4%, and 101.6%) was recorded within the landholdings of Tryfonivka, Sadok, and Starosillia.

In terms of contamination levels, the elementary plots are distributed as follows: 70.27% of the areas are characterized by an absence of contamination, 22.54% by a low level, 6.23% by a moderate level, 0.73% by a medium level, and only 0.23% by an increased level. Low-level contamination was identified in specific areas of fields No. 8, 10, 11, 15, 17, 19, and 21, located within Starosillia, Velyka Oleksandrivka, Sadok, Krynychanka, Sukhyi Stavok, and Chornobaivka. Simultaneously, in several fields (No. 1, 4, 7, 13, 16, 18, 20, 24), a combination of low and increased contamination levels was established. In certain fields (No. 1 – Kamiane; No. 9 – Tryfonivka), a more complex distribution structure is observed, where medium values are present alongside low and increased levels. In plot No. 12 (Velyka Oleksandrivka), a medium contamination level (1.45 mg·kg^{-1}) was recorded (Figure 8). No exceedances of the maximum allowable concentration (MAC = 5 mg·kg^{-1}) for mobile cobalt compounds were detected.

The obtained distribution of contamination levels for Cu, Ni, and Co reflects both differences in their geochemical behavior within the soil environment and the heterogeneity of potential source inputs. The extremely low proportion of areas with low-level copper contamination (0.9%) indicates the absence of significant anthropogenic load by this element within the studied territory. This aligns with the high capacity of Cu for complexation with organic matter and its strong fixation by the soil-absorbing complex, which limits its mobility and accumulation in mobile forms (Kabata-Pendias, 2011; Alloway, 2013). Nickel (with 5.4% of areas showing low and increased contamination) is characterized by more pronounced spatial-local heterogeneity, due to its relatively higher mobility and sensitivity to fluctuations in acid-base conditions. This may indicate a predominantly point-source nature of input and a weakly expressed anthropogenic component (Alloway, 2013; Adriano, 2001). The most significant is the distribution of cobalt, for which approximately 30% of the areas are characterized by low, moderate, medium, and increased contamination levels. This may be

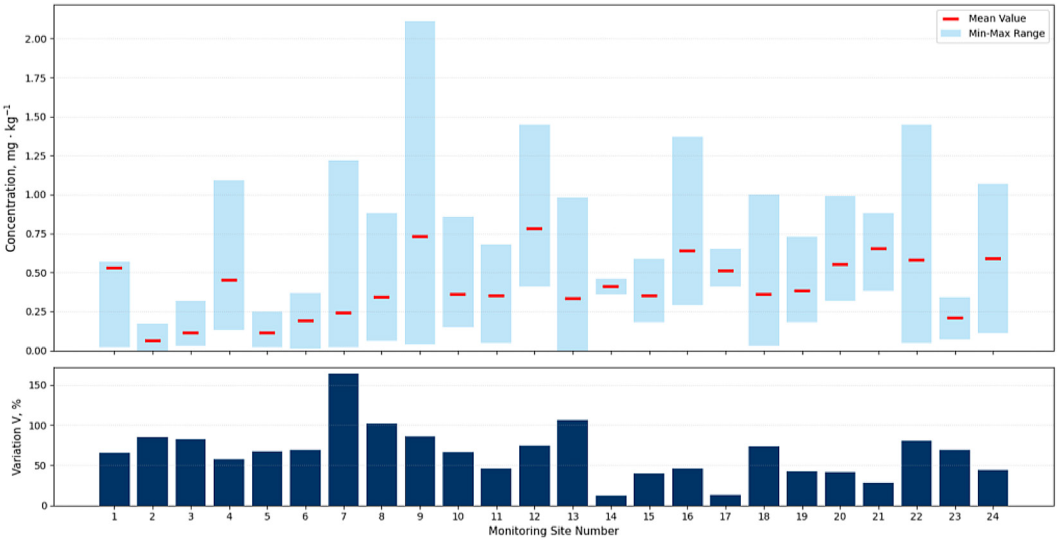

Figure 8. Content of cobalt mobile compounds

associated both with its association with Fe–Mn oxides and intra-profile redistribution, as well as with a more diffuse anthropogenic impact manifesting across a significant portion of the study area (Kabata-Pendias, 2011).

The absence of mobile form accumulation for Cu, Ni, and Co is generally explained by the combination of the high buffering capacity of chernozems, significant organic matter and carbonate content, and intensive sorption of heavy metals by the clay-humus complex, which substantially limits their migration and bioavailability (Kabata-Pendias, 2011; Alloway, 2013; Adriano, 2001).

Content of mobile forms of hazard Class III and IV heavy metals

Manganese (Mn) and iron (Fe) belong to hazard Class III and IV heavy metals, respectively. Mechanical disturbance of the soil profile, explosive processes, thermal impact, and local changes in redox conditions can lead to a temporary transition of Fe and Mn into more mobile forms (Fe^{2+}, Mn^{2+}), manifesting as a local increase in their content (Adriano, 2001; Alloway, 2013). At the same time, the accumulation of these elements is restrained by the high buffering capacity of chernozems, significant organic matter content, and the dominance of iron oxides, which effectively immobilize Fe, Mn, and other metals (Kabata-Pendias, 2011). Thus, military actions act as a trigger for short-term mobilization of Fe and Mn due to the disruption of soil structure and redox equilibrium.

The weighted average content of mobile iron compounds in the soils of the studied plots was 2.24 mg·kg^{-1} and varied within the range of 0.68–4.86 mg·kg^{-1}. The coefficient of variation (57.0%) indicates a high level of spatial heterogeneity of the indicator. The highest values were recorded in plots No. 4 (4.86 mg·kg^{-1}), No. 6 (4.27 mg·kg^{-1}), No. 7 (3.93 mg·kg^{-1}), and No. 9 (3.92 mg·kg^{-1}), located within the landholdings of Blahodatne, Nezlamne, and Tryfonivka villages.Within the elementary plots, the variation of the indicator was significantly wider – from 0.18 to 12.23 mg·kg^{-1} of soil, and the coefficient of variation ranged from 11.2% to 91.9%. The highest variability (91.9%, 87.8%, and 85.6%) was recorded within the landholdings of the urban-type settlement of Velyka Oleksandrivka and Nezlamne village (Figure 9).

Maximum allowable concentrations for mobile iron compounds in soils are not regulated; however, the obtained values correspond to background (natural) levels characteristic of the region's soils.The weighted average content of mobile manganese compounds in the soils of the studied plots was 52.44 mg·kg^{-1}, which corresponds to a low level of contamination. Within the fields, the indicator varied widely – from 9.59 to 226.64 mg·kg^{-1}; the coefficient of variation was 48.2%, indicating high spatial heterogeneity. The highest values were recorded in plots No. 22 (226.64 mg·kg^{-1}), No. 9 (129.37 mg·kg^{-1}), and No. 7 (105.83 mg·kg^{1}), located within the landholdings of Kamiane and Tryfonivka villages. Within the elementary plots, the variation was

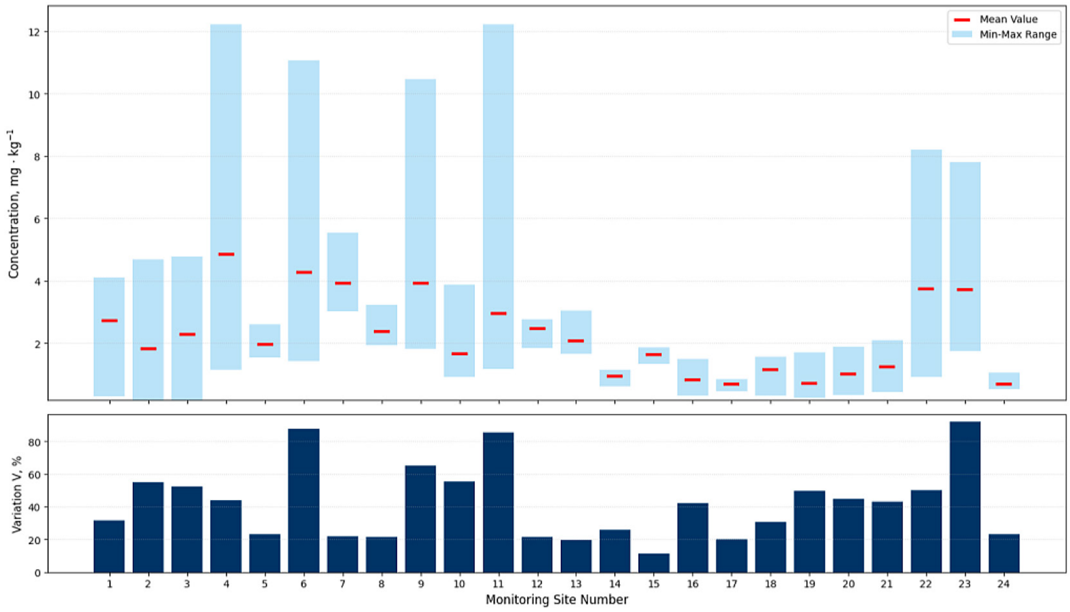

Figure 9. Content of iron mobile compounds

even wider (0.57–443.3 mg·kg^{-1}), and the coefficient of variation ranged from 14.5% to 79.2%. The highest variability was established within the landholdings of Barvinok, Tryfonivka, and Kamiane villages (79.2%, 75.9%, and 64.3%, respectively).

In the contamination structure, 60.74% of the area is characterized by an absence of contamination, and 28.11% by a low level, while the total share of plots with increased, high, and very high levels is approximately 3.5%. At the same time, according to the supply indicators, a significant part of the territory (38.54%) is characterized by a very high manganese content.The spatial distribution is mosaic in nature: in specific fields No. 2, 3, 10, and 15 (Ivanivka, Novopetrivka, Starosillia, and Sadok villages), a combination of different contamination levels is observed, whereas in fields No. 9 and No. 22, the most complex structure was recorded, featuring a full spectrum of levels – from low to very high (Tryfonivka and Kamiane villages) (Figure 10).

Exceedances of the maximum allowable concentration (140 mg·kg^{-1}) were established in fields No. 7, No. 9 (Tryfonivka village), and No. 22 (Kamiane village), where values reached 161.37–443.32 mg·kg^{-1} (1.1–3.2 times the MAC).

The increased sensitivity of Mn as an indicator of soil environment changes identified in this study differs from most works where Pb is considered the primary marker of military impact. Under typical shooting range conditions, lead accumulates in the upper horizons due to the corrosion of metal fragments and is characterized by low mobility and strong binding with organic matter and Fe and Mn oxides (Adriano, 2001; Kabata-Pendias, 2011).

In the studied chernozems, Mn exhibits higher sensitivity to changes in environmental conditions due to its redox-controlled behavior. Under reducing conditions, insoluble Mn (III–IV) oxides transition into mobile Mn (II) forms, leading to its mobilization and local accumulation (Shuman, 1988; McBride, 1994). Similar processes are noted in other studies where Mn is considered an indicator of changes in the soil redox regime, especially under conditions of excess moisture or in depressed relief elements.

Geospatial analysis of the integrated pollution index for mobile heavy metal forms

The conducted geospatial analysis of the integrated pollution index (Z_c) revealed pronounced spatial heterogeneity in the distribution of heavy metals in the soils. It was established that only 9.2% of the plots had no exceedances, while the remainder recorded an increase in the content of at least one heavy metal. Most fields were characterized by a mottled (variegated) pattern of contamination, indicating the uneven influence of local factors and varying intensities of anthropogenic load. Orange and red colors predominate on the maps (Z_c 1.5–3.0 and >3.0), indicating an overall

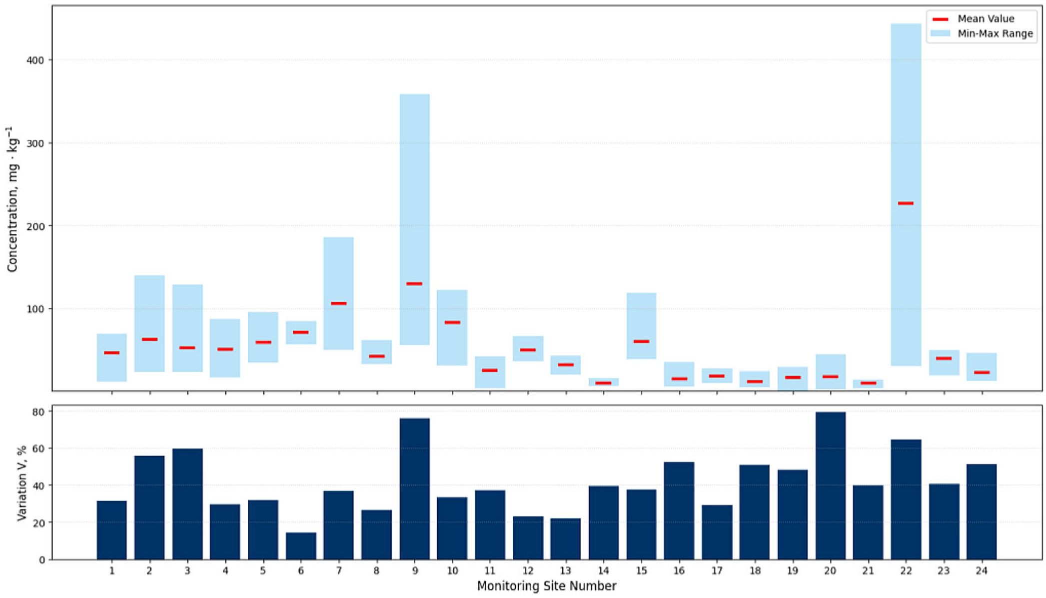

Figure 10. Content of manganese mobile compounds

complicated state of the soil mass. The most affected are fields No. 1, 3, 4, 9, 18, and 22, where high values of the integrated index cover significant areas. A relatively better state is observed in fields No. 5, 12, 14, and 23, although local hotspots of medium-level contamination are recorded there as well (Figure 11).

The mosaic nature of contamination is typical for areas subjected to point-source military impact (ammunition explosions, equipment fragments), where local geochemical anomalies are formed (Solokha et al., 2024; Altahaan and Dobslaw, 2024; Kucher and Honcharova, 2025). Similar patterns have been confirmed for post-conflict agro-landscapes, where contamination remains localized (Broomandi et al., 2020; Yashchenko et al., 2025; Altahaan and Dobslaw, 2024). The primary source of lead is ammunition, and its accumulation is caused by corrosion, mechanical destruction, and weathering of metal fragments (Kim et al., 2021), which forms stable anomalies in the upper soil horizons (Alloway, 2013; Kabata-Pendias, 2011; Chen et al., 2019). Nickel and manganese originate from steel and alloy materials of military equipment and ammunition (Jenkins et al., 2006; Kabata-Pendias, 2011; Alloway, 2013; Abdallah et al., 2023), whereas cadmium is characterized by high migratory capacity and is redistributed within the soil profile (Kabata-Pendias, 2011; Alloway, 2013). Lead, conversely, accumulates in the upper horizons due to strong binding with organic matter and Fe and Mn oxides (Adriano, 2001; McBride, 1994).

Additionally, agrotechnical measures (plowing, cultivation), fertilization, and natural moisture processes facilitate the dispersion and redistribution of heavy metals, reducing the contrast of local anomalies (Alloway, 2013; Kabata-Pendias, 2011; McLaughlin et al., 2011). In this context, organic fertilizers may either immobilize or mobilize metals depending on the environmental conditions (Adriano, 2001).

The absence of critical exceedances of the maximum allowable concentration is explained by the combination of natural soil self-purification, the high buffering capacity of chernozems, and agrotechnical influence, which promotes the stabilization of metals within the soil matrix (Kabata-Pendias, 2011; Alloway, 2013).

The geoaccumulation index (I_{geo}) reflects the degree of anthropogenic transformation of the soil environment. It is based on a logarithmic scale, where each subsequent value corresponds to a doubling of the element's concentration relative to the background level. Unlike Z_c, I_{geo} is less sensitive to minor fluctuations and emphasizes significant deviations, allowing for the identification of geochemical anomalies. The anthropogenic impact is visualized according to the following criteria:Class 0 ($I_{geo} \leq 0$): corresponds to the background state; Class 1 ($0 < I_{geo} \leq 1$): uncontaminated to moderately contaminated; Class 2 ($1 < I_{geo} \leq 2$): moderately contaminated;Class 3 ($2 < I_{geo} \leq 3$): moderate to strongly contaminated; Class 4 ($3 < I_{geo} \leq 4$): strongly contaminated;Class 5 ($4 < I_{geo} \leq$

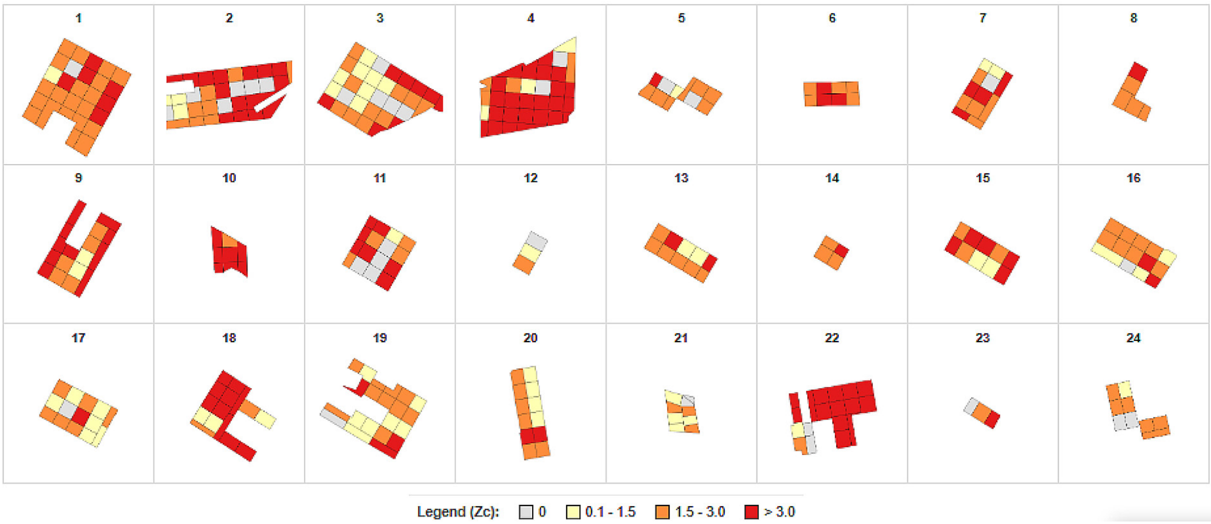

Figure 11. Spatial distribution of the integrated pollution index (Z_c) at the elementary plot level

5): strong to extremely strongly contaminated; Class 6 (I_{geo} > 5): extremely strongly contaminated.As shown in Figure 12, the geoaccumulation index (I_{geo}) for heavy metal forms enables the visualization of local technogenic anomalies.

The persistence of local geochemical anomalies indicates a risk of secondary contamination and underscores the necessity of accounting for spatial heterogeneity in the environmental assessment of land. The re-integration of metals into the biogeochemical cycle is possible through profile migration, plant uptake, and trophic transfer (Alloway, 2013; Kabata-Pendias, 2011; McLaughlin et al., 2011). Studies of World War I territories in the Verdun sector showed heavy metal exceedances even 90 years after military operations (Bausinger et al., 2007), demonstrating the long-term nature of such processes. Consequently, a two-year period following the active phase of hostilities is insufficient for a definitive assessment of soil stabilization. The currently recorded relatively moderate level of contamination may reflect the initial stage of soil system transformation. In the long term, slow metal migration within the soil profile, the gradual release of elements from ammunition corrosion products, and changes in redox conditions under the influence of agrotechnical measures may lead to a delayed increase in the concentrations of mobile heavy metal forms. The identified anomalies (No. 23 – Ni; No. 22, 9, 7 – Mn; No. 10 – Pb) may persist as long-term sources of secondary contamination due to the presence of equipment fragments and ammunition. Therefore, the results obtained should be regarded as a baseline (reference) level for future monitoring.

For post-conflict agro-landscapes, an integrated approach to soil remediation is appropriate, aimed at reducing heavy metal bioavailability and stabilizing the soil system. One of the most effective directions is phytoremediation, which involves the use of accumulator and stabilizer plants, specifically Brassica juncea, Helianthus annuus, and Lolium perenne. The effectiveness of this approach is due to the plants' capacity for phytoextraction and phytostabilization of metals within the rhizosphere, as confirmed by numerous studies (Ali et al., 2013; Mahar et al., 2016; Yadav et al., 2018). Phytoremediation is considered an environmentally safe and economically viable method for reducing the bioavailability of Cd, Pb, Zn, and Ni in soils.

The application of organic materials (manure, compost, green manure, biochar) plays a crucial role, as it facilitates the formation of stable organo-mineral complexes, reduces the mobility of Pb, Cd, and Zn, and improves the soil's agro-physical properties (Beesley et al., 2011; Lehmann and Joseph, 2015; Ahmad et al., 2014). Liming is an effective agrotechnical measure for acidity regulation, reducing the bioavailability of heavy metals through the formation of poorly soluble hydroxides and carbonates, particularly for Cd and Pb (Kabata-Pendias, 2011; Alloway, 2013). Deep soil mixing may be used to temporarily reduce pollutant concentrations in the upper horizon; however, this measure does not eliminate contamination but merely alters its spatial distribution (McLaughlin et al., 2011). Additionally,

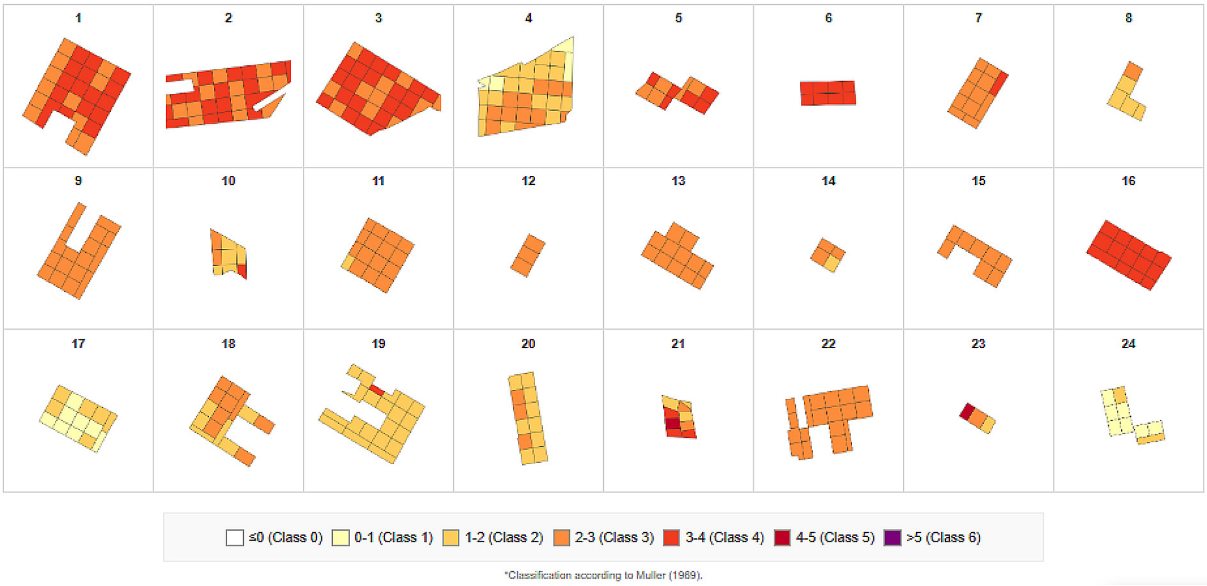

Figure 12. Spatial distribution of the geoaccumulation index I_{geo} at the elementary plot level

chemical immobilization using phosphates, zeolites, clay minerals, and Fe and Mn oxides is effective in reducing heavy metal mobility and limiting their uptake by plants (Mench et al., 2010; Bolan et al., 2014).

An essential management element is the spatial zoning of territories based on contamination levels, which involves restricting the cultivation of food crops in areas with elevated metal content and reorienting toward industrial crops (FAO, 2018; Chen et al., 2019). Systematic soil monitoring using GIS technologies is of key importance, enabling the detection of local anomalies, assessment of change dynamics, and evidence-based land resource management (Zhang et al., 2020).

The most effective strategy is an integrated one, combining phyto- and bioremediation, organic fertilization, chemical stabilization, and spatially-oriented land resource management.

CONCLUSIONS

The conducted research demonstrated that the content of mobile heavy metal forms in the agricultural soils of the Kherson Oblast is characterized by pronounced spatial heterogeneity, resulting from a combination of natural factors (texture, humus content, soil reaction) and anthropogenic factors, specifically the consequences of military operations and subsequent land use.

Studies conducted two years after the active phase of hostilities revealed that, overall, the level of soil contamination does not exceed critical regulatory values. At the same time, local anomalies of elevated concentrations of certain elements, particularly nickel and manganese, were identified, indicating the technogenic nature of the contamination. Most of the studied elements (copper, cobalt, zinc) remain at background or slightly elevated levels. Mobile forms of lead and cadmium pose a potential ecological risk; however, their concentrations generally do not exceed maximum allowable values. The low cadmium content in the upper soil layer may be due to its high migratory capacity, biological uptake by plants, and redistribution within the soil profile. The absence of significant exceedances of maximum allowable concentrations is explained by natural soil self-purification processes (sorption, migration, dilution), as well as agrotechnical measures – mechanical tillage, fertilization, and restoration of vegetative cover – which facilitate the reduction of local concentrations.

The most hazardous contamination hotspots are confined to specific fields: No. 23 (nickel), No. 22, No. 9, and No. 7 (manganese), and No. 10 (lead), where regulatory exceedances or maximum concentrations were recorded. This confirms the localized nature of the technogenic impact associated with military operations. These areas were subjected to mortar, artillery, and rocket fire, were mined, and contained craters, traces of fires, and remnants of military equipment and ammunition. Thus, the ecological state of the studied soils is relatively stable overall; however, the pronounced mosaic distribution of pollutants necessitates continued monitoring, detailed mapping, and ecological risk assessment to ensure the safe use of agricultural lands.

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