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Monitoring of the Geochemical State of Soils in Bombturbation Zones of the Kyiv Prydniprovnia¹

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Based on the primary results of comprehensive field and laboratory studies within selected territorial hromadas of the Kyivska, Chernihivska, and Zhytomyrska oblasts, certain aspects of the state of soil cover damaged as a result of the 2022 military actions are highlighted. A methodology for indexing and sampling deposits within bombturbation zones is proposed that considers the spatial and morphological characteristics of the objects of study to assess potential contamination by harmful substances. Detailed results of field studies at five key sites near the settlements of Hoholiv, Shestovytsia, Yablunivka, Lypivka-Makariv, and Vorzel are presented, along with laboratory test results for the content of heavy metals (20) and biogenic elements (59). It has been established that explosions cause not only mechanical disturbances of the soil profile but also noticeable chemical changes, particularly a local increase in the concentrations of Fe, Cu, Ni, Zn, and Pb, which are most frequently observed in samples from the bottoms and rims of craters. The content of biogenic elements also occasionally exhibits distinct spatial differences within individual craters studied (Hoholiv, Shestovytsia, Yablunivka). Most often, exceedances (relative to background values) of phosphorus, potassium, iron, and sulfur are recorded, occurring in samples from both the bottoms and rims of craters and from the surrounding area. However, it is worth noting that there are cases (Makariv-Lypivka, Vorzel) where it is not possible to establish direct links between increased concentrations of the studied elements and bombturbations. Furthermore, at none of the studied objects were exceedances of the concentrations of the studied elements recorded that would be harmful to human health. The identified spatial distribution patterns of disturbed soil masses, heavy metals, and biogenic elements enable assessment of the redistribution of natural and technogenic substances resulting from military impacts. The research results highlight the necessity of monitoring contamination and assessing long-term environmental consequences for lands affected by combat operations.

Keywords: *soil contamination, bombturbation, heavy metals, biogenic elements, environmental impact of war, Russian invasion of Ukraine.*

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Relevance of the research topic

Full-scale combat operations in Ukraine cause significant destruction of infrastructure and substantial changes to the natural components of the environment, among which the soil cover is one of the most important. Explosions of munitions cause mechanical disturbances to the soil cover, changes in the structure of genetic profiles, active movement of soil masses, and likely chemical contamination with heavy metals and other technogenic impurities. In the scientific literature, there is a limited number of comprehensive studies based on systematic field and laboratory observations of such processes. Therefore, the issues of assessing the actual scale of military impact on soils, the degree of soil contamination, identifying patterns of pollutant transport and accumulation, and substantiating potential environmental and economic consequences remain extremely relevant. The data obtained in this direction are necessary to develop scientifically based proposals for monitoring, restoration, and safe-use programs for lands affected by combat operations.

Current state of research

International studies in various regions of the world, including Croatia, Kosovo, Spain, France, the USA, Canada, Syria, Iraq, Kuwait, Vietnam, Brazil, and other countries, record a significant impact of military actions on the soils of individual territories affected by armed conflicts or located within the impact zones of military training grounds [1–8, *et al.*]. Regarding the development of approaches to assessing the impact of military actions on soil conditions in Ukraine, a significant number of studies have already been devoted to this issue [9–16, *et al.*]. Assessment of the impact of military actions on the state of soils focuses on three groups of changes: physical or morphological (compaction, destruction of structure, formation of explosion craters, erosion); chemical (contamination with heavy metals, residues of explosive substances, petroleum products, combustion products, depleted uranium, etc.); biological (transformations of the state of soil biota, disruption of ecosystem functions of soils in biogeocenoses, etc.).

We see the task of our work as presenting and analyzing new factual materials on the content of heavy metals and individual biogenic elements in objects affected by military actions on the territory of Ukraine. The studies conducted are in line with

the global trend in research on similar topics [2, 5, 7–8 *et al.*].

The aim and methods of the research

The aim of the research is to assess the extent of damage and contamination of soils in the Kyiv Prydniprovya resulting from military actions, based on comprehensive field and analytical data on the content of heavy metals and several biogenic elements. The publication uses methods of analysis, synthesis, and interpretation of analytical materials and literary sources, summarizes the results of specific field studies, and propose theoretical developments regarding the methodology for soil sampling from bombturbation zones for laboratory studies (a new author's approach); laboratory studies on the content of heavy metals and a number of biogenic elements in soil deposits were conducted to assess the impact of military actions on the state of the soil cover.

To assess the degree of soil damage and contamination by military actions, monitoring of the current environmental conditions was carried out, and laboratory geochemical studies of soil samples were conducted within selected territorial hromadas of the Kyiv Prydniprovya (*Fig. 1*). For these territories, spatial identification of bombturbation sites was performed using remote sensing data, totaling 17.362 units. The results obtained were used to create a series of map schemes [17–19], which were adapted for field research using the QField application.

The selection of key study sites within specific hromadas is due to the fact that their territories were the scene of intense combat at the beginning of the full-scale aggression of the rf, and they are currently de-occupied, which provides the opportunity for full-scale field research. In particular, in September–October 2024 (2.5 years after the de-occupation of the territories), routes were identified and established to 48 objects of bombturbation zones (craters, shell holes), their precise geolocation was performed, monitoring of their current state was carried out, along with photo and video documentation at the time of the study, a detailed landscape description of the objects and the surrounding area was completed, and samples of soil deposits were taken for various types of analysis (183 samples in total).

In this publication, the results of soil-geochemical studies of only five bombturbation objects near the settlements of Hoholiv (Kyivska oblast), Shestovytsia (Chernihivska oblast), Vorzel, Lypiv-

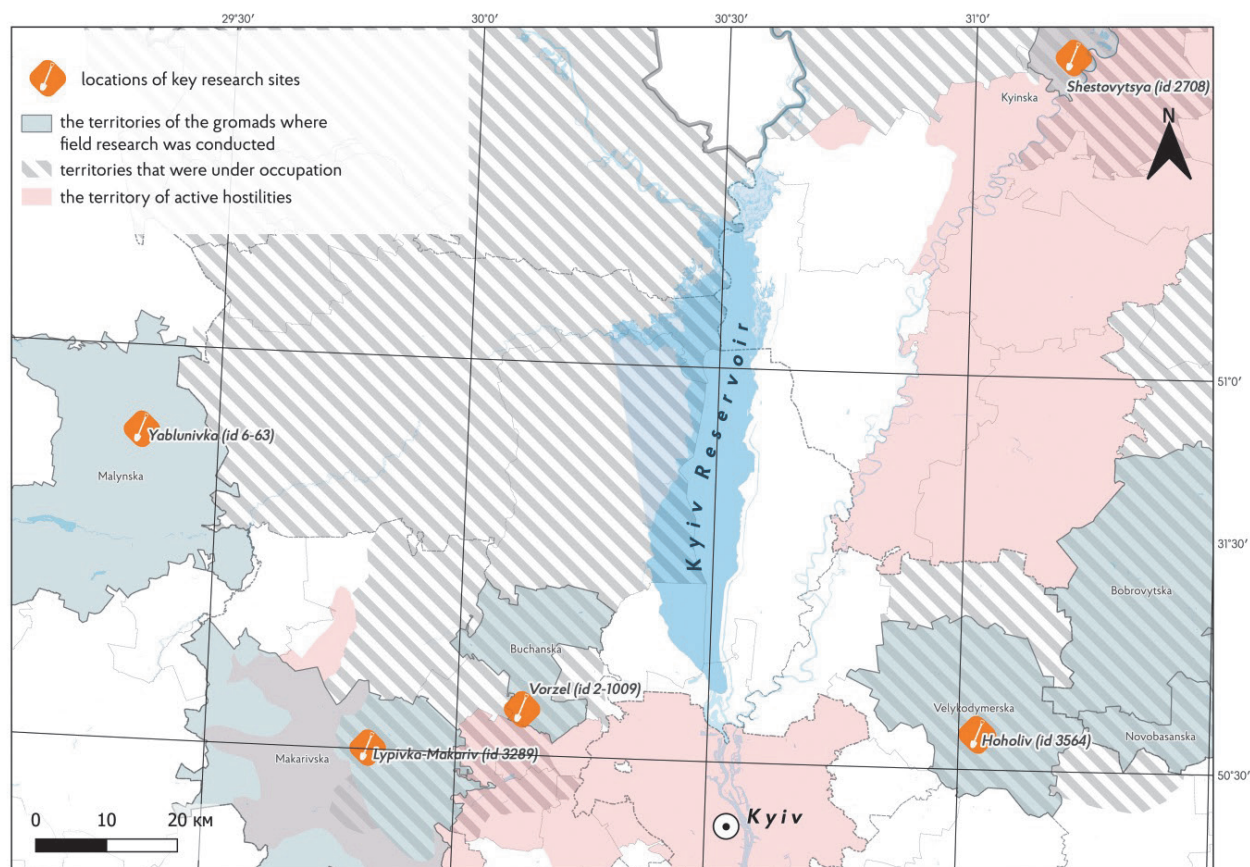


Fig. 1. Territorial hromadas within which field studies were conducted

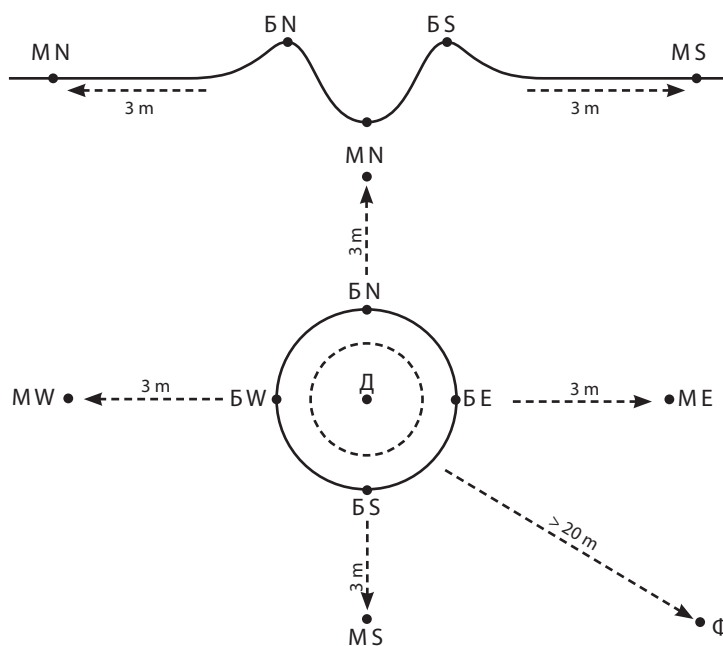


Fig. 2. Scheme of sampling and indexing of soil material samples during field studies of bombturbations: A – cross-section of the studied crater from north to south; B – sampling scheme around the object of study, top view.

● — sampling locations; 3 m — distance from the crater wall to the sampling locations; Д — crater bottom;
 БН — northern side of the crater rim; БS — southern side of the crater rim; БE — eastern side of the crater rim;
 БW — western side of the crater rim; МN — northern side of the area around the crater; МS — southern side of the area;
 МE — eastern side of the area; МW — western side of the area; Φ — background sample.

ka-Makariv (Kyivska oblast), and Yablunivka (Zhytomyrska oblast) are presented. This selection is because they are located in different physical-geographical conditions, are geographically distant from each other, and are clearly identifiable on the ground.

From each crater, 9 soil deposit samples were collected using a soil sampler for laboratory studies. To identify the spatial attribution of the samples, the following indexing system was developed: from the bottom of the crater (index Д); from the four cardinal points of the crater walls (indices BN—northern side; BS—southern side; BE—eastern side, and BW—western side); from the four cardinal points at a distance of at least 3 m from the edges of the crater (the so-called “area” around the crater, indices MN—northern side; MS—southern side; ME—eastern side, and MW—western side). Another tenth sample (and sometimes more) was taken from the background soil, at a distance of at least 20 m from the bombturbations, on an identical landform (index Ф) (**Fig. 2**). Background samples were taken from a depth of 0.2–0.3 m.

The proposed scheme for sampling soil samples according to the cardinal points around the studied bombturbations, in our opinion, firstly, provides information on the characteristics of the spatial distribution of the studied substances, and secondly, ensures higher reliability of the results obtained due to an increased sample size and repeatability of laboratory analyses of soil material samples taken under similar conditions that were or could have been affected by military actions. At the same time, it is worth noting that the author's scheme considered the relevant regulatory legal act regarding the procedure for soil sampling on agricultural lands cleared of explosive objects [20].

Laboratory studies of heavy metal content (20 samples) were performed in the laboratory of the Department of Chemistry and Expertise of Food Products of the Educational and Scientific Institute of Biology, Chemistry, and Bioresources of the Yuriy Fedkovych Chernivtsi National University. Soil samples were previously dried to an air-dry state and crushed using an agate mortar. For heavy metal extraction, acid leaching of soils with a mixture of concentrated hydrochloric and nitric acids was performed under two-stage heating to 165°C for 30 min in a Multiwave 5000 microwave oven (Anton Paar, Austria). After decomposition, the samples were brought to a final volume of

25 ml with a 1 M nitric acid solution (extra-pure grade) and filtered through a “blue ribbon” paper filter. Measurements were performed by atomic absorption spectroscopy (AAS) using an S-115M flame spectrophotometer. For the measurements, an “acetylene-air” flame in absorption mode was used. Four samples taken from the crater rims (as well as four from the area around the craters) were combined into a single average sample for laboratory studies.

Analysis of soil for biogenic element content (59 samples) was conducted in the allelopathy scientific department of the M. M. Gryshko National Botanical Garden of the NAS of Ukraine. Laboratory studies were performed according to the method of H. Ya. Rinkis on an ICAP 6300 DUO inductively coupled plasma spectrometer (Thermo Fisher Scientific, USA). For the extraction of macro- and microelements, methods of agrophysical and agrochemical soil analysis were used [21].

In assessing the potential contamination of soils within bombturbation zones, we correlated the laboratory results with official documents and the literature. Regarding exceedances of maximum permissible concentrations of hazardous substances in soils, according to the Resolution of the Cabinet of Ministers of Ukraine dated December 15, 2021, No. 1325 “On approval of standards for maximum permissible concentrations of hazardous substances in soils, as well as the list of such substances” [22], they are as follows, mg/kg of soil, considering the background (clarke): Copper (mobile form — 3); Manganese (total content — 1500 / mobile form — 140); Nickel (mobile form — 4); Zinc (total content — 23); Lead (total content — 32 / mobile form — 6); Cadmium (total content — 3 / mobile form — 0.7); Cobalt (mobile form — 5); Nitrates (by NO₃) (total content — 130); Sulfates (by SO₄) (total content — 160); Phosphorus (by P₂O₅) (total content — 200); Potassium chloride (total content — 560). Regarding the content of biogenic elements in soils, the study also considered that, according to literature data, the following indicators are optimal for agricultural crops on the territory of Ukraine [23], mg/l: NH₄ — 10–15; NO₃ — 90–120; P — 110–130; K — 210–250; Ca — 3200–4000; Mg — 70–90; Fe — 50–80; S — 20–30; Mn — 15–20. According to the reaction of the medium, the soil cover can be acidic (pH < 7.0), neutral (pH ≈ 7), or alkaline (pH > 8.0). The humus

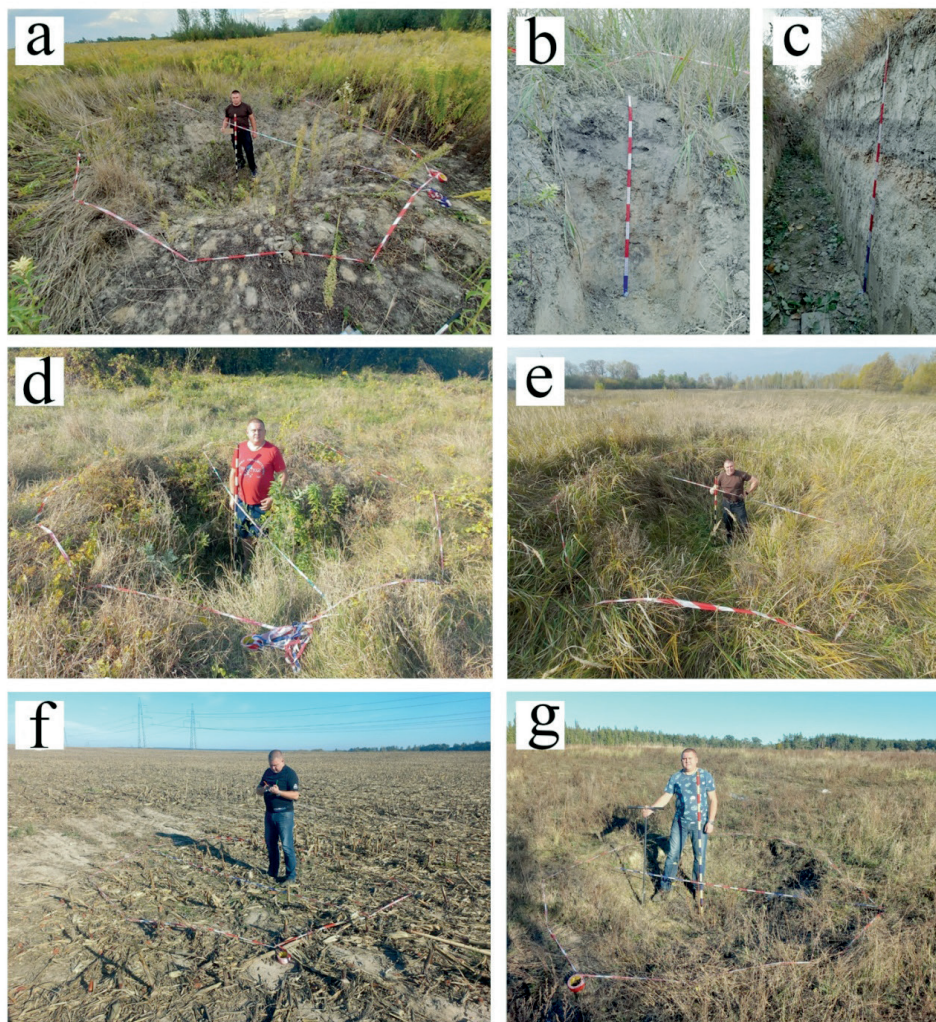


Fig. 3. Field studies of bombturbation zones within individual hromadas of the Kyiv Prydniprovya (author's photos):

- a* — crater (id 3564) to the north of the village of Hoholiv (*Velyka Dymierka hromada*);
- b* — soil profile in the north-western wall of the crater (id 3564);
- c* — soil profile in the northern wall of a defensive fortifications trench;
- d* — crater (id 2708) to the north of the village of Shestovytsia (*Kyinska hromada*);
- e* — crater (id 6-63) to the east of the village of Yablunivka (*Malynska hromada*);
- f* — crater (id 3289) to the south of the village of Lypivka (*Makarivska hromada*);
- g* — crater (id 1009) to the north of the village of Vorzel (*Buchanska hromada*).

content in soils depends on the genetic soil types and the nature of economic use.

Presentation of the main material with substantiation of the obtained scientific results

Results of field and laboratory studies of the crater near the village of Hoholiv (id 3564)

The crater is located on the northern outskirts of the village of Hoholiv of the Velykodymierka territorial hromada (coordinates 50.54425, 31.0348) (*Fig. 3a*). The depth of the crater is 1.4 m, and the

diameter from north to south is 5.5 m. Field studies date: September 16, 2024. Nine deposit samples (No. 30–38) were taken from the crater for laboratory analysis; one background soil sample (No. 39) was also taken, and four more samples (No. 40–43) were collected from the genetic horizons of the soil profile cleared in the north-western wall of the crater (*Fig. 3 b*).

Within the genetic soil profile cleared in the north-western wall of the crater, five genetic horizons were identified: HP (0.0–0.2 m), H(e) (0.2–0.5 m), Hpi (0.5–0.85 m), Phk (0.85–1.05 m), and Pk (1.05–1.2 m). From the last four genetic horizons, as already mentioned, samples were taken

for laboratory studies. No sample was taken from the surface horizon (HP), which is an analog of the crater rim (from which four other samples had already been taken).

A brief morphogenetic description of the genetic horizons of the soil profile cleared in the north-western wall of the crater is as follows: HP (0.0–0.2 m) — a surface horizon newly formed as a result of the explosion, bluish-light-grey (10YR/6/2)², loose, permeated with fine roots of herbaceous plants, sandy loam-light loamy, weakly carbonate — barely perceptibly effervesces with a 10% hydrochloric acid solution; H(e) (0.2–0.5 m) — the darkest-colored light loamy horizon in the soil profile (10YR/4/1), loose, light loamy, with a blocky-granular structure, in some places lightened areas with hidden SiO₂ dusting appear, does not effervesce with a 10% hydrochloric acid solution; Hpi (0.5–0.85 m) — greyish-light-brown (10YR/6/3) sandy light-medium loam, the most compacted compared to the horizons above and below, with a nut-like structure, leached of carbonates, heterogeneous, with brown spots of iron accumulation and humus spots and streaks along vertical cracks between structural units; Phk (0.85–1.05 m) — greyish-pale (10YR/5/2) light loam, loose, heterogeneous, with spots of iron accumulation and humus, effervesces with a 10% hydrochloric acid solution; Pk (1.05–1.2 m) — bluish-greyish-pale (10YR/6/4) sandy loam-light loam, crumbly-loose, actively effervesces with a hydrochloric acid solution. It is worth noting that, in general, the profile of the soil studied in the crater does not appear typical, undisturbed, or solid. Signs of mass loosening and disruption of soil structure are noticeable, and morphons with different (at least in color) soil material are present in the genetic horizons.

A similar soil profile is observed 300 m to the south-east of the crater, in the trenches of defensive fortifications (coordinates 50.5426, 31.0383), likely constructed during combat operations (**Fig. 3c**), thereby confirming the distribution of this genetic soil type in this area. A comparison of the two soil profiles provides an opportunity to identify the thickness of the soil masses that ended up on the surface after the explosion. For instance, in the defensive trench, in the upper part of the soil profile, lightened light loamy-sandy loam deposits with a thickness of about 35–38 cm are clearly distin-

guished, which overlay the dark-colored natural chernozem material and reached the surface as a result of the construction of defensive fortifications. In the soil profile of the crater, we also observe a 20–25 cm layer of lightened deposits, which, as a result of the explosion, formed the so-called crater rim and covered the natural surface soil horizon.

Differences in the structure of genetic horizons are also noticeable. While the soils in the trench have a clearly defined horizontal layering, the soil profile from the crater is characterized by a more mosaic structure (the presence of humus-colored morphons in the structure of the middle and lower genetic horizons), which, however, is not necessarily a consequence of explosive activity but may be a natural feature caused by the activity of soil fauna. This issue requires further clarification.

In the sample taken from the bottom of the crater near the village of Hoholiv (id 3564), according to the data of laboratory studies on the content of heavy metals (**Table 1**), relatively increased (compared to values from other samples) indicators of Cu (10.77 mg/kg), Fe (13625 mg/kg), Ni (27.94 mg/kg), Zn (42.16 mg/kg), and Pb (53.56 mg/kg) are recorded. High lead indicators were also recorded in the average sample of the area (36.59 mg/kg).

According to the results of the analysis of biogenic element content in soil samples from the crater near the village of Hoholiv (id 3564) (**Table 2**), exceedances (compared to the background soil sample) of phosphorus (P) content were recorded in samples from the bottom and the rim of the crater, as well as in the sample from the northern part of the area. The highest values (109 mg/kg) were found in the southern and western parts of the crater rim.

The potassium (K) content in all studied samples from the crater is higher than the background level (by 2–3 or more times). The highest values, exceeding 100 mg/kg, were recorded in deposits from the crater bottom, from the northern and eastern crater rims, and the northern area. A high (84 mg/kg) relative K content was also found in samples taken from the southern and western sides of the crater rim. In general, the average K content in the area samples is lower than in the crater samples, but it is 2 or more times higher than the background. A tendency toward a decrease in potassium content with increasing distance from the crater center was observed.

² Here and hereafter, soil color was determined visually using the Munsell Soil Color Charts (Munsell Color, 1990/2010).

Table 1. Heavy metal content in soil samples from the crater near the village of Hoholiv (id 3564)*

Sample	Sample weight, g	Moisture, %	Soil, g	Metal content, mg/kg							
				Cu	Fe	Mn	Ni	Zn	Pb	Cd*	Co*
Г-6-3564-Д	0.301	8.13	0.277	10.77	13625	109.75	27.94	42.16	53.56	< 0.5	< 0.5
Г-6-3564-Б	0.308	2.95	0.299	7.12	10971	141.89	8.70	30.82	< 2.0	< 0.5	< 0.5
Г-6-3564-М	0.302	3.46	0.292	6.17	9570	148.80	11.28	32.12	36.59	< 0.5	< 0.5
Г-6-3564-Ф	0.303	4.43	0.290	6.55	13422	245.79	17.98	31.42	< 2.0	< 0.5	< 0.5

* — values below the detection limit.

Table 2. Biogenic element content in soil samples from the crater near the village of Hoholiv (id 3564)

Element	30 Д	31 БН	32 БС	33 БЕ	34 БУ	35 МН	36 МС	37 МЕ	38 МВ	39 Ф
NH ₄	25	25	30	20	30	30	20	20	20	30
NO ₃	0	0	0	0	0	0	0	0	0	0
P	82	54.5	109	27.5	109	54.5	27.5	27.5	27.5	27.5
K	110	102.6	84	102.6	84	102.6	56.1	74.7	65.4	37.2
Ca	25656	5831	4331.6	4831.4	7163.8	4331.6	3831.8	2832.2	5664.4	5664.4
Mg	914.4	812.8	609.6	508	711.2	914.4	711.2	609.6	1625.6	812.8
Fe	562.5	250	125	137	250	124	125	125	250	250
S	62.5	12.5	37.5	12.5	12.5	12.5	12.5	12.5	12.5	25
Mn	140	120	100	100	140	140	100	70	270	180
pH	7.49	7.4	6.91	7	7.14	7.07	6.89	6.56	7.2	7.19
C % humus	1.6	2.1	3.1	1.1	1.1	2.1	1.6	1.6	2.1	1.6
EC	233	148	202	227	236	327	323	293	223	350
HCO ₃	0.32	0.16	0.18	0.44	0.48	0.48	0.64	0.58	0.42	0.32

Table 3. Legend for cell background coloring in tables of heavy metal and biogenic element content in the analyzed samples

Background values			
Exceed background values by:		Lower than background values by:	
1.5–2 times		1.5–2 times	
3 times		3 times	
4 times		4 times	
5 or more times		5 or more times	

Table 4. Biogenic element content in samples from genetic horizons of the natural soil profile in the north-western wall of the crater (id 3564) near the village of Hoholiv

Element	39 Ф	40 H(e)	41 Hpi	42 Phk	43 Pk
NH ₄	30	10	20	10	10
NO ₃	0	0	0	0	0
P	27.5	54.5	109	109	82
K	37.2	121.2	158.7	130.5	186.6
Ca	5664.4	5331.2	3831.8	4931.4	5481.1
Mg	812.8	1422.4	1219.2	9245.6	9448.8
Fe	250	250	562.5	312.5	137.5
S	25	12.5	25	50	50
Mn	180	120	50	0	0
pH	7.19	7.37	7.37	7.68	7.8
C % humus	1.6	1.6	1	1	1
EC	350	250	217	265	246
HCO ₃	0.32	0.34	0.48	0.8	0.88

Table 5. Heavy metal content in soil samples from the crater near the village of Hoholiv (id 3564)*

Metal content, mg/kg											
Sample	Sample weight, g	Moisture, %	Soil, g	Cu	Fe	Mn	Ni	Zn	Pb	Cd*	Co*
Ш-2708-Д	0.301	19.51	0.242	9.57	28735	125.56	28.88	33.29	< 2.0	< 0.5	< 0.5
Ш-2708-Б	0.306	11.05	0.272	9.79	27256	165.56	20.71	35.48	19.40	< 0.5	< 0.5
Ш-2708-М	0.3	13.74	0.259	14.47	41435	278.30	24.93	41.37	< 2.0	< 0.5	< 0.5
Ш-2708-Ф	0.301	11.38	0.267	9.33	17592	373.38	16.24	41.71	< 2.0	< 0.5	< 0.5

* — values below the detection limit.

Table 6. Biogenic element content in soil samples from the crater near the village of Shestovytsia (id 2708)

Element	48 Д	49 БН	50 БС	51 БЕ	52 БВ	53 МН	54 МС	55 МЕ	56 МВ	57	58	59	60 Ф
NH ₄	10	20	20	20	10	10	20	15	10	20	15	15	20
NO ₃	15	3.8	4.5	3.8	3.8	3.8	7.5	3.8	7.5	3.8	15	3.8	3.8
P	54.5	54.5	82	54.5	54.5	82	82	54.5	54.5	54.5	54.4	54.5	54.5
K	62.5	79.1	78	60.7	129.4	158	116.1	73.3	77.3	64	94.5	87.3	84
Ca	4664.8	4998	6330.8	5831	4165	4998	6997.2	5164.6	6830.6	3165.4	6664	12828	4664.8
Mg	609.6	609.6	609.6	101.6	101.6	101.6	101.6	508	914.4	406.4	203.2	101.6	711.2
Fe	1500	1500	1500	1750	1500	1750	2250	1500	2250	500	3750	1500	500
S	50	37.5	25	37.5	37.5	37.5	37.5	37.5	37.5	37.5	50	37.5	37.5
Mn	100	100	140	120	80	100	210	100	160	100	140	120	140
pH	6.32	6.1	6.24	6.15	6.18	6.1	6.21	6.69	6.32	6.55	6.53	7.21	6.8
C % humus	2.1	10.8	9.3	11.7	10.8	3.9	10.1	3.6	10.1	2.1	3.9	1.1	3.1
EC	795	360	278	318	265	190	192	245	195	135	191	225	297
HCO ₃	0.24	0.48	0.48	0.48	0.48	0.34	0.34	0.56	0.24	0.32	0.34	0.8	0.56

Table 7. Heavy metal content in soil samples from the crater near the village of Yablunivka (id 6-63)

Metal content, mg/kg											
Sample	Sample weight, g	Moisture, %	Soil, g	Cu	Fe	Mn	Ni	Zn	Pb	Cd*	Co*
Я-6-63-Д	0.301	9.59	0.272	12.07	6304	50.00	17.32	38.52	9.46	< 0.5	< 0.5
Я-6-63-Б	0.301	6.91	0.280	0.00	3025	70.38	13.61	22.79	< 2.0	< 0.5	< 0.5
Я-6-63-М	0.304	8.84	0.277	2.77	3055	155.96	15.78	24.76	< 2.0	< 0.5	< 0.5
Я-6-63-Ф	0.301	6.26	0.282	4.36	2927	156.14	9.76	22.06	< 2.0	< 0.5	< 0.5

* — values below the detection limit.

Table 8. Biogenic element content in soil samples from the crater near the village of Yablunivka (id 6-63)

Element	152 Д	153 БН	154 БС	155 БЕ	156 БВ	157 МН	158 МС	159 МЕ	160 МВ	161 Ф
NH ₄	60	50	20	15	50	20	20	20	30	20
NO ₃	15	15	15	22.5	22.5	15	15	22.5	22.5	15
P	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5
K	122.2	151.4	138.3	140.7	132.8	124.7	107.3	112.4	120.8	78.4
Ca	666.4	499.8	333.2	666.4	333.2	333.2	333.2	166	833	333.2
Mg	101.6	101.6	101.6	101.6	101.6	101.6	101.6	152.4	101.6	101.6
Fe	375	137.5	125	125	137.5	250	250	250	250	125
S	37.5	25	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Mn	60	80	60	70	100	80	80	120	120	90
pH	4.08	4.91	5.38	5.39	5.37	4.67	4.68	4.43	5.11	4.41
C % humus	0.8	1	0.8	1	1.6	1	1.6	1.6	1.6	1.6
EC	166	238	141	180	216	196	237	219	180	149
HCO ₃	0.08	0.08	0.08	0.12	0.12	0.08	0.08	0.08	0.08	0.08

Table 9. Heavy metal content in soil samples from the crater near the Makariv settlement — Lypivka village (id 3564)*

Metal content, mg/kg											
Sample	Sample weight, g	Moisture, %	Soil, g	Cu	Fe	Mn	Ni	Zn	Pb	Cd*	Co*
М-Л-3289-Д	0.302	10.84	0.269	9.68	7187	338.97	12.41	26.78	9.19	< 0.5	< 0.5
М-Л-3289-Б	0.304	9.15	0.276	14.89	5779	259.03	22.47	36.11	< 2.0	< 0.5	< 0.5
М-Л-3289-М	0.3	8.03	0.276	6.79	6507	272.38	16.08	26.66	< 2.0	< 0.5	< 0.5
М-Л-3289-Ф	0.301	4.87	0.286	7.29	8517	205.92	15.44	25.43	52.52	< 0.5	< 0.5

* — values below the detection limit.

Table 10. Biogenic element content in soil samples from the crater near the Makariv settlement — Lypivka village (id 3289)

Element	123 Д	124 БН	125 БС	126 БЕ	127 БВ	128 МН	129 МС	130 МЕ	131 МВ	132 Ф
NH ₄	25	60	20	10	15	15	15	20	20	40
NO ₃	15	11.3	15	15	7.5	7.5	7.5	7.5	15	7.5
P	109	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	109
K	47.1	47.7	63.5	50.2	60.9	112.4	132.8	110	71.4	73.8
Ca	1999.2	1666	1832.6	2165.8	1499.4	1499.4	1832.6	1832.6	1166.2	1832.6
Mg	101.6	203.2	304.8	101.6	101.6	101.6	406.4	304.8	101.6	203.2
Fe	562.5	625	625	625	562.5	625	625	500	500	500
S	25	25	25	100	25	62.5	100	100	50	37.5
Mn	350	250	240	300	210	300	300	210	240	180
pH	6.64	5.72	5.71	6.21	5.71	5.41	5.87	6.29	6.04	4.98
C % humus	1.6	2.1	2.6	2.6	1.6	2.1	2.1	2.1	2.6	2.1
EC	270	170	208	391	139	165	175	233	164	104
HCO ₃	0.16	0.16	0.08	0.2	0.12	0.12	0.08	0.16	0.16	0.16

Table 11. Heavy metal content in soil samples from the crater near the Vorzel settlement (id 2-1009)*

Metal content, mg/kg											
Sample	Sample weight, g	Moisture, %	Soil, g	Cu	Fe	Mn	Ni	Zn	Pb	Cd*	Co*
В-2-1009-Д	0.302	6.44	0.283	0.00	4495	113.23	8.16	17.44	< 2.0	< 0.5	< 0.5
В-2-1009-Б	0.3	6.53	0.280	8.23	3453	154.15	12.08	24.11	51.58	< 0.5	< 0.5
В-2-1009-М	0.306	5.81	0.288	21.89	4032	137.45	17.79	36.76	< 2.0	< 0.5	< 0.5
В-2-1009-Ф	0.3	3.98	0.288	8.14	4297	167.39	14.68	26.76	< 2.0	< 0.5	< 0.5

* — values below the detection limit.

Table 12. Biogenic element content in soil samples from the crater near the Vorzel settlement (id 2-1009)

Element	92 Д	93 БН	94 БС	95 БЕ	96 БВ	97 МН	98 МС	99 МЕ	100 МВ	101 Ф (0.1-0.2 m)	102 Ф (0.2-0.3 m)	103 Ф (0.5-0.6 m)
NH ₄	30	40	40	30	30	30	30	40	35	30	20	20
NO ₃	7.5	7.5	3.8	3.8	7.5	3.8	3.8	7.5	11.3	3.8	3.8	3.8
P	109	54.5	54.5	82	82	82	82	82	54.5	82	82	54.5
K	296.5	340.6	252.5	282.7	303.5	237.9	267.7	252.3	315.3	256.5	263.1	469.2
Ca	1332.8	1832.6	1832.6	2332.4	1999.2	2165.8	2165.8	1999.2	1666	1666	999.6	833
Mg	101.6	101.6	101.6	101.6	304.8	101.6	101.6	203.2	203.2	508	101.6	101.6
Fe	750	1000	875	1125	1250	1000	625	1250	875	1250	1000	375
S	37.5	25	37.5	25	25	37.5	37.5	25	37.5	37.5	37.5	25
Mn	120	180	160	270	180	240	160	210	210	240	120	120
pH	6.09	6.01	6.08	6.01	5.92	6.16	5.83	5.91	5.89	5.78	5.45	5.74
C % humus	1.1	1.5	1.6	2.1	1.6	2.1	2.1	1.6	2.1	1.1	1.1	1
EC	324	153	137	105	109	113	134	106	132	77	87	51
HCO ₃	0.16	0.16	0.16	0.16	0.08	0.16	0.16	0.16	0.08	0.08	0.08	0.16

An exceedance of Fe and S content (by more than 2 times) was detected at the bottom of the crater. Interestingly, a similar trend of increasing sulfur content with depth is observed in the soil profile cleared in the north-western wall of the crater (**Fig. 3b**). However, the iron content there decreases with depth, also by approximately 2 times compared to background values.

The distribution of Ca perfectly illustrates the pattern of dispersal of carbonate deposits resulting from the explosion. Thus, the highest values (almost 5 times higher than the background) are characteristic of the crater bottom, which is understandable given the presence of parent rocks in the form of carbonate loess-like loams. All other indicators do not differ significantly from the background; however, the Ca content in the area samples is clearly lower than in the rim samples. Among the latter, samples from the western and northern parts of the crater rim stand out, with higher carbonate content than in the background sample. This is explained by the ejection of carbonate parent deposits from lower-lying horizons onto the soil surface by the explosion.

In the sediment samples taken from the genetic horizons of the soil profile cleared in the north-western wall of the crater (id 3564) (**Table 4**), an increased content (compared to background values) of Phosphorus (by 2–4 times) and Potassium (by 2–4 times) is recorded throughout the entire soil profile, as well as Sulfur (by 2 times) in the two lower genetic horizons. A slightly increased iron content (up to 562.5 mg/kg) was recorded in the Hpi horizon, which, in principle, is in good agreement with the natural properties and morphological appearance of this genetic horizon.

The distribution graphs of calcium and iron along the profile are generally consistent with the natural features of grey forest soils (grey podzolic soils). In particular, the exceedance of Ca and Mg cations by ten or more times is quite characteristic of parent loess-like loams, while an increase in Fe cation content is typical for horizons with signs of illuvial genesis, which were obviously diagnosed by the nut-like structure in the subsurface soil horizon from the defensive trench. The humus content in the area and background samples ranges from 1.6% to 2.1%, which is generally typical for the surface horizons of grey forest soils (Albic/Haplic Luvisols) and correlates with the map of agro-industrial soil distribution of the Velykodymerska hromada [23].

Results of field and laboratory studies of the crater near the village of Shestovytsia (id 2708)

The investigated crater is located 1.5 km north of the village of Shestovytsia, Kyinska territorial hromada, Chernihivska oblast, 500 meters east of the Kyinka-Shestovytsia highway (coordinates 51.4054, 31.1963) (**Fig. 3d**). Field experiments were conducted on September 16, 2024. The depth of the crater is 1.05 m, and the diameter from north to south is 5.1 m. Nine sediment samples (Nos. 48–56) were taken from the crater (id 2708) for laboratory analysis; another three samples (Nos. 57–59) were taken from neighboring locations within agricultural fields where remote sensing data indicated former craters, along with one background sample (No. 60).

The results of the analysis of heavy metal content in samples from the crater near the village of Shestovytsia (id 2708) (**Table 5**) record relatively uniform Cu content indicators (9.33 mg/kg background value, 9.57 and 9.79 mg/kg — copper content in samples from the bottom and the rim of the crater, respectively; a slightly increased content, at the level of 14.47 mg/kg, was recorded in the average sample of the area). The Fe content in the samples from the crater and the surrounding area is higher than the background value by 9,664–23,843 mg/kg. The Ni content in samples from the crater bottom and the surrounding area is also higher than the background value by 4.47–12.64 mg/kg. At the same time, a decrease in manganese content toward the bottom of the crater is recorded. A relatively increased Pb content (up to 19.40 mg/kg) was recorded in the crater rim compared to the laboratory results of other samples.

The results of laboratory studies on biogenic element content (**Table 6**) show an increase (relative to background values) in Fe content in all samples taken from the crater (id 2708). It is also interesting that in two out of three samples (Nos. 58 and 59) taken from agricultural fields at locations where craters were previously identified, the iron content is also increased. Compared to background values, the iron content is increased by 3–4 times and, in sample No. 58, by more than 7 times.

The results of the analysis of K content appear interesting. When comparing the K content at the bottom and three parts of the crater rim (northern, southern, and eastern), the indicators there are slightly lower (by 6.0–13.3 mg/kg) compared to the

background (84 mg/kg). At the same time, the K content results around the crater, in samples 53 MN and 54 MS, as well as from the crater rim (No. 52 BW), are higher than the background (by 74, 32.1, and 45.4 mg/kg, respectively).

A slight increase in P content (by 17.5 mg/kg) was recorded in samples taken from the southern part of the crater rim and the northern and southern parts of the area surrounding the crater. The P content results in all other samples are identical to the background, at the level of 54.5 mg/kg.

An increased (compared to background values) phosphorus content of 12.5 mg/kg was detected at the bottom of the crater, as well as in sample No. 58.

It is also worth noting the high humus content (up to 11.7%) in the vast majority of samples from the surface soil horizons, which is generally characteristic of chernozem soils (Gleyic Chernic Phaeozems (Pachic)) of meadow genesis and correlates with the map of agro-industrial soil distribution of the Kyivska hromada [23].

Results of field and laboratory studies of the crater near the village of Yablunivka (id 6-63)

The investigated crater (id 6-63) is located 150 m east of the main street of the village of Yablunivka, Malynska territorial hromada, Zhytomyrska oblast (coordinates 50.8913, 29.3448) (**Fig. 3e**). Field experiments were conducted on October 28, 2024. The depth of the crater is 1.4 m, and the diameter from north to south is 5.0 m. Nine sediment samples (Nos. 152–160) and one background sample (No. 161) were taken from the crater (id 6-63) for laboratory analysis.

The results of the analysis of heavy metal content in samples from the crater near the village of Yablunivka (id 6-63) (**Table 7**) record increased indicators (compared to background values) of certain heavy metals in the sample from the crater bottom:

Cu = 12.07 mg/kg (with background values of 4.36 mg/kg);
Fe = 6,304 mg/kg (with background values of 2,927 mg/kg);
Ni = 17.32 mg/kg (with background values of 9.76 mg/kg);
Zn = 38.52 mg/kg (with background values of 22.06 mg/kg);

Pb = 9.46 mg/kg (with background values < 2.0 mg/kg).

It is also worth noting that, compared to background indicators, the contents of Fe, Ni, and Zn are relatively higher in samples from the rim and around the crater.

The results of laboratory studies on biogenic element content (**Table 8**) show an increase in K content by 1.5–2 times over background values (from 107.3 to 151.4 mg/l, with a background content of 78.4 mg/l). It is worth noting that the K content is generally higher in samples taken from the crater bottom and rim.

A Fe and S content increased by 3 times was detected in the samples taken from the crater bottom.

The Ca and Mg contents are low and approximately uniform across all investigated samples, which is characteristic of natural podzolic soils. The humus content fluctuates within the range of 0.8–1.6% and is generally lower within the crater bottom and rim. The soil is classified as acidic, as the pH of the investigated samples ranges from 4.08 at the crater bottom to 4.91–5.39 on the crater rims and 4.43–5.11 in the surrounding area, with a background value of 4.41.

According to morphological and geochemical indicators, the soils are weakly podzolic soils on fluvioglacial deposits (Albic Retisols), which correlates with the map of agro-industrial soil distribution for the Malyn hromada [23].

Results of field and laboratory studies of the crater near the Makariv settlement — Lypivka village (id 3289)

The investigated crater (id 3289) is located on the southern outskirts of the village of Lypivka, Makarivska territorial hromada, Kyivska oblast, 70 m east of the Makariv-Lypivka-Havronshchyna road junction (coordinates 50.5004, 29.8246). Field experiments were conducted on October 22, 2024. The crater is situated within an agricultural field where corn was grown; at the time of the study, the corn had been harvested. The crater is partially plowed over, but it is obviously traceable by microrelief features. Its depth is about 0.1 m, and the diameter from north to south is 3.2 m (**Fig. 3f**). Nine sediment samples (Nos. 123–131) and one background sample (No. 132) were taken from the crater for laboratory analysis.

The results of the analysis of heavy metal content in samples from the site of the former crater near the Makariv settlement — Lypivka village (id 3289) (**Table 9**) are rather indistinct. The highest content of Cu (14.89 mg/kg), Ni (22.47 mg/kg), and Zn (36.11 mg/kg) was recorded in samples from the crater rim; Mn (338.97 mg/kg) was found at the crater bottom; Fe (8,517 mg/kg) and Pb (52.52 mg/kg) were recorded in the background sample.

Since the crater near the Makariv settlement — Lypivka village (id 3289) is almost completely plowed over due to agricultural activities, the results regarding biogenic element content (**Table 10**) show little variation, and the gradients of changes are generally insignificant. Only the S content in samples from the surrounding area and the eastern part of the crater rim is higher than the background, reaching up to 3 times in certain samples (126 BE, 129 MS, and 130 ME). Conversely, the P and K content is often lower. Compared to background values, the phosphorus content in samples from the rim and the area surrounding the crater is reduced by a factor of 4. A slightly lower potassium content was recorded in samples from the bottom and the rim of the crater.

The humus content in the investigated soil samples ranges from 1.6–2.6%. The Ca and Mg content indicators range from 1,166.2–2,165.8 mg/l and 101.6–304.8 mg/l, respectively. According to morphological and geochemical indicators, the soils are represented by sod-medium-podzolic soils on fluvioglacial deposits (Albic Retisols), which correlates with the map of agro-industrial soil distribution of the Makarivska hromada [23].

Results of field and laboratory studies of the crater near the Vorzel settlement (id 2-1009)

The investigated crater (id 2-1009) is located 350 m south of the road junction between the villages of Nemishaieve, Vorzel, and Myrotske, Buchanska territorial hromada, Kyivska oblast (coordinates 50.5569, 30.1286) (**Fig. 3g**). Field experiments were conducted on October 21, 2024. The depth of the crater is 0.4 m, and the diameter from north to south is 3.7 m. Nine sediment samples (Nos. 92–100) and three background soil samples from depths of 0.1–0.2 m, 0.2–0.3 m, and 0.5–0.6 m (Nos. 101–103) were taken from the crater (id 2-1009) for laboratory analysis.

The results of the analysis of heavy metal content in samples from the crater near the Vorzel settlement (id 2-1009) (**Table 11**) are quite uniform, without a clearly defined spatial distribution of increased heavy metal content. In particular, the highest Fe content (4,495 mg/kg) was recorded in samples from the crater bottom (in general, iron content indicators are fairly uniform); Pb (51.58 mg/kg) — from the crater rim; Cu (21.89 mg/kg), Ni (17.79 mg/kg), and Zn (36.76 mg/kg) — from the area surrounding the crater; Mn (167.39 mg/kg) — in the background sample.

The results of laboratory studies on biogenic element content in crater id 2-1009 (**Table 12**) do not record significant gradient changes in the investigated indicators. Deviations from background values are generally minimal, except for a slightly increased P content at the bottom of the crater. The humus content in the investigated soil samples ranges from 1.1–2.1%. Calcium (Ca) content ranges from 833–2,165.8 mg/l, and Magnesium (Mg) — from 101.6–508 mg/l.

According to morphological and geochemical indicators, the soils are represented by medium podzolic soils on fluvioglacial deposits (Albic Retisols), which correlates with the map of agro-industrial soil distribution of the Bucha hromada (Map..., 2018).

Conclusions

The studies conducted in September–October 2024 provided new data on the impact of military operations on soil cover in specific territorial hromadas of the Kyiv Prydniprovya. These efforts aimed to diagnose and assess the degree of contamination of damaged soils two and a half years after the start of Russia's full-scale aggression against Ukraine.

To diagnose and assess potential contamination with harmful substances, methodology for indexing and sampling sediments within bombturbation zones was proposed. This methodology accounts for the spatial and morphological characteristics of the investigated objects.

In total, 183 samples were collected during the 2024 field studies. Of these, 59 samples from five key sites near the settlements of Hoholiv, Shestovytsia, Yablunivka, Lypivka–Makariv, and Vorzel were analyzed for heavy metal and biogenic element content. The results demonstrate certain spatial differences in the concentrations of heavy metals and biogenic elements.

In most of the investigated craters, a local increase in Cu, Fe, Ni, Zn, and Pb concentrations is observed, most frequently in samples from the crater bottoms and rims. This may indicate the influx of these chemical components into the soil mass resulting from munitions detonation. The most pronounced spatial differentiation and exceedances of background concentrations were recorded in the craters near Hoholiv, Shestovytsia, and Yablunivka.

The content of biogenic elements also frequently exhibits significant spatial gradients within individual craters investigated (Hoholiv, Shestovytsia, Yablunivka). Exceedances in phosphorus, potassium, iron, and sulfur are most commonly recorded, occurring in samples from the crater bottoms and rims, as well as from the surrounding area. In several cases, substantial propagation gradients from the center of the explosion to the periphery were recorded, enabling reconstruction of the movement patterns of soil masses or individual elements. However, it is worth noting that there are cases (Makariv–Lypivka, Vorzel) where direct links between increased concentrations of the studied elements and bombturbations could not be established. In some cases, this is due to the wrapping of funnels during agricultural work (Makariv–Lypivka), which, in turn, leads to the mixing of sediments. In others, it depends on the granulometric composition of the soils that were damaged by explosions. For example, in soils of sandy granulometric composition, the spatial-morphological pattern of the distribution of heavy metals and biogenic elements looks less clear (Vorzel, Lypivka–Makariv), in contrast to more loamy soils, which, due to the increased content of colloidal particles, have a higher buffer capacity and better retain pollutants in case they enter the soil masses (Hoholiv, Shestovytsia).

Furthermore, no concentrations of the studied elements exceeding levels harmful to human health were recorded at any of the investigated sites. This suggests that nature, through soil formation pro-

cesses, is quite successful at neutralizing substances harmful to human health—at least within the scope of the studied objects (noting that samples were collected 2.5 years after active hostilities). At the same time, the issue of potential pollutant migration (including through groundwater) requires further research.

The studies also indicated that explosions lead to the active displacement of parent soil-forming materials to the surface. This is traceable both morphologically and through laboratory data, indicated by a sharp increase in Ca and Mg concentrations on the rims of craters formed in soils developed on carbonate loess-like rocks (Hoholiv).

The results confirm that the impact of explosions on the soil profile is not only mechanical (disruption of genetic horizons, destruction of primary microrelief, mixing of sediments) but also chemical, as enrichment with technogenic components was recorded in the analyzed samples. Simultaneously, it is important to note that excessive heavy metal contamination was not detected at the sites studied.

Thus, the conducted research demonstrates the sensitivity of soils to military operations and highlights the necessity for systematic monitoring of contamination. This is essential for assessing current environmental risks and forecasting potential short- and long-term consequences for the agricultural use of affected lands.

The scientific novelty of the article lies in the presentation and analysis of new empirical data concerning the degree of soil damage and contamination resulting from military operations. This is based on comprehensive field and analytical data on the content of heavy metals and a range of biogenic elements in soil sediments, derived from primary studies of five key sites within the Kyiv Prydniprovnia. Furthermore, the author's methodology for selecting soil samples from bombturbation sites is proposed.

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На основі первинних результатів комплексних польових та лабораторних досліджень, в межах окремих територіальних громад Київської, Чернігівської та Житомирської областей, висвітлено деякі аспекти стану ґрунтового покриву пошкодженого внаслідок воєнних дій 2022 р. Запропоновано до використання методу індексації та відбору зразків відкладів в межах зон бомбтурбацій, яка враховує просторові та морфологічні особливості об'єктів дослідження для оцінки потенційного забруднення шкідливими речовинами. Наведено детальні результати польових досліджень для п'яти ключових ділянок біля населених пунктів Гоголів, Шестовиця, Яблунівка, Липівка-Макарів, Ворзель, а також результати лабораторних досліджень зразків на вміст важких металів (20) та біогенних елементів (59). Установлено, що вибухи спричиняють не лише механічні порушення ґрунтового профілю, а й помітні хімічні зміни, зокрема локальне підвищення концентрацій Fe, Cu, Ni, Zn та Pb, які найбільш часто спостерігаються у зразках із дна та брівок воронки. Вміст біогенних елементів також іноді демонструє яскраві просторові відмінності в межах окремих досліджених воронки (Гоголів, Шестовиця, Яблунівка). Найчастіше реєструється перевищення (у порівнянні із фоновими значеннями) фосфору, калію, заліза та сірки, які приурочені як до зразків із дна та брівки воронки, так і до зразків з прилеглої місцевості. Однак, варто відзначити, що зустрічаються випадки (Макарів-Липівка, Ворзель), коли не вдається зафіксувати прямі зв'язки між підвищеними концентраціями досліджених елементів та бомбтурбаціями. Окрім цього, на жодному із досліджених об'єктів не зафіксовано шкідливі для здоров'я людини перевищення концентрацій досліджуваних елементів. Виявлені закономірності просторового розповсюдження порушених ґрунтових мас, важких металів та біогенних елементів дозволяють оцінити спричинений воєнними впливами характер перерозподілу природних і техногенних речовин. Результати дослідження підкреслюють необхідність моніторингу забруднення та оцінки довгострокових екологічних наслідків для земель, що зазнали впливу бойових дій.

Ключові слова: забруднення ґрунтів, бомбтурбації, воєнні дії, важкі метали, біогенні елементи, вплив війни на довкілля, вторгнення Росії в Україну.

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