ISSN 2518-7325 (Online), ISSN 2306-1677 (Print)
Land Management, Cadastre and Land Monitoring
Received: 20.04.2026; Accepted: 14.05.2026; Published: 30.06.2026;
http://dx.doi.org/10.31548/zemleustriy2026.02.10

UDC 631.171:631.4

ASSESSMENT OF THE ECOLOGICAL AND AGROCHEMICAL CONDITION OF AGRICULTURAL LANDS BASED ON AUTOMATED SOIL SAMPLING

O. Hryshchenko, *Candidate of Agricultural Sciences,*
E-mail: grischenkoel@ukr.net, ORCID: 0000-0002-1241-7183
State Institution "Institute for Soil Protection of Ukraine"
Ye. Butenko, *Candidate of Economic Sciences, Associate Professor,*
E-mail: Butenko@nubip.edu.ua, ORCID: 0000-0002-5923-5838
National University of Life and Environmental Sciences of Ukraine
V. Hryshchenko, *Student,*
E-mail: grischenkovik@gmail.com, ORCID: 0009-0003-8550-2033
National University of Life and Environmental Sciences of Ukraine,
State Institution "Institute for Soil Protection of Ukraine"
V. Bozhok, *Student,*
E-mail: hiz23-v.bozhok@nubip.edu.ua, ORCID: 0009-0002-1646-4937
National University of Life and Environmental Sciences of Ukraine
D. Vynnyk, *Student,*
E-mail: hiz23-d.vynnyk@nubip.edu.ua, ORCID: 0009-0008-1698-942X
National University of Life and Environmental Sciences of Ukraine

Abstract. *The article assesses the ecological and agrochemical condition of agricultural lands using the automated soil sampling system Bodenprobenehmer N2006. The relevance of applying automated soil monitoring technologies under* *conditions of intensified agricultural production, the development of precision farming, and the necessity to evaluate lands affected by military impacts is substantiated.*

The study was conducted on a land plot covering 279.4 hectares located outside the village of Bryhadyrivka, Izium Territorial Community, Izium District, Kharkiv Region, Ukraine. To assess the condition of the soil cover, 60 composite samples were collected from the 0–30 cm arable layer, with the territory divided into elementary plots of up to 5 hectares each.

Laboratory analyses included the determination of the main agrochemical and ecological-toxicological soil indicators, particularly soil solution reaction (pH), humus content, easily hydrolyzable nitrogen, mobile phosphorus and potassium compounds, micronutrients, and heavy metals. Statistical processing of the results involved calculating weighted average values, variation ranges, and coefficients of variation.

The soils of the studied area were found to be characterized by a near-neutral soil reaction and high humus content, indicating the preservation of their natural fertility potential. At the same time, an imbalance in certain agrochemical indicators was identified, including low availability of easily hydrolyzable nitrogen, very low content of mobile zinc compounds, and low manganese content. The ecological-toxicological assessment revealed an increased concentration of mobile cadmium compounds across a significant part of the study area, as well as slight and moderate levels of lead contamination within certain elementary plots.

The obtained results indicate the spatial heterogeneity of agrochemical and toxicological indicators, which may be associated both with the natural mosaic structure of the soil cover and with localized military-technogenic impacts. The expediency of using automated soil sampling systems for developing electronic maps of soil indicators, monitoring contamination, planning reclamation measures, and implementing precision farming elements is substantiated.

***Keywords**: soil, ecological and agrochemical assessment, automated soil sampling, Bodenprobenehmer N2006, agrochemical indicators, heavy metals, military impact, precision farming.*

Relevance of the Study. Contemporary soil assessment in Ukraine is conducted under conditions characterized by the combined influence of agricultural intensification, climate change, soil degradation, and the large-scale military impact on land resources. This creates an urgent need to improve the accuracy, efficiency, and spatial resolution of soil monitoring systems [1–5].

Traditional soil assessment methods, including manual soil sampling, soil bonitation, and ecological-agrochemical certification, remain an important methodological foundation; however, they do not always provide sufficient speed and representativeness of data acquisition required for modern land resource management [6, 8, 11]. This issue is particularly critical for lands affected by military operations, where contamination and degradation processes often exhibit localized and mosaic spatial patterns [4, 5].

The military impact on soils is manifested through mechanical destruction of the soil profile, formation of trenches, craters, and dugouts, overcompaction of the arable layer by heavy machinery, pyrogenic effects caused by fires, as well as potential contamination by heavy metals, explosive residues, fuels and lubricants, and corrosion products from military equipment [4, 5]. Under such conditions, the standard density of soil sampling may be insufficient for detecting localized contamination hotspots.

At the same time, the development of precision agriculture requires the creation of digital maps of agrochemical and toxicological soil indicators, which serve as the basis for variable-rate fertilizer application, planning of land reclamation measures, and sustainable land use management [6–8]. Therefore, the implementation of automated soil sampling systems is highly relevant, as such systems provide GPS-referenced sampling locations, reduce the influence of the human factor, increase the productivity of field operations, and enable the integration of results into GIS platforms [9–11].

Consequently, the relevance of this research is determined by the necessity to improve methodological and technological approaches to the ecological and agrochemical assessment of agricultural lands, particularly those affected by military activities. The application of automated soil sampling technologies represents a promising tool for оперативний monitoring, identification of spatial heterogeneity in soil properties, assessment of contamination risks, and ensuring effective post-war restoration of soil fertility [9–11].

Analysis of Recent Research and Publications. The issues of qualitative assessment, bonitation, and monitoring of land resources have been extensively addressed in the works of numerous domestic and foreign scholars. In particular, the studies of I. O. Udovenko and S. O. Chornyi reveal the theoretical and methodological foundations of soil quality assessment as a basis for determining the value of natural resources, rational land use, and planning measures aimed at improving soil fertility [3, 12].

Special attention in contemporary scientific literature is devoted to the digitalization of the agricultural sector and the transition toward precision agriculture systems. In the works of V. R. Cherlinka and V. S. Zakharovskyi, the directions of automation of calculations in qualitative soil assessment are substantiated [13]. D. V. Fedasiuk and M. O. Kostiuk investigate the possibilities of applying machine learning technologies for predicting the physical properties of soils within smart farming systems [7].

International studies also confirm that the development of precision agriculture is directly associated with the use of spatially detailed soil data, GPS navigation, GIS platforms, remote sensing technologies, and digital mapping. In particular, Alex McBratney, Brendan Whelan, Tihomir Ancev, and Johan Bouma consider precision agriculture as a management system based on the spatial variability of soil properties and requiring the integration of field, laboratory, and cartographic data [14].

An important area of modern research concerns the improvement of soil sampling strategies. B. S. Farmaha and co-authors emphasize that soil sampling constitutes the foundation for assessing soil pH, nutrient status, and decision-making regarding lime and fertilizer application, while the number and scheme of sampling points should account for the spatial variability of soil cover [15]. Research conducted by J. R. M. R. Gonçalves and co-authors demonstrates that different sampling approaches in precision agriculture — including grid sampling, zone-based approaches, and soil electrical conductivity-based sampling — may produce different fertilization recommendations, thereby confirming the importance of selecting a representative survey design [16].

A promising research direction is the application of automated and sensor-based technologies for soil data acquisition. V. I. Adamchuk, J. W. Hummel, M. T. Morgan, and S. K. Upadhyaya summarized the capabilities of mobile soil sensors for precision agriculture and highlighted that such technologies enable an increase in measurement density while reducing the cost of obtaining spatial soil property data [17]. At the same time, the technical specifications of the Bodenprobenehmer N2006 automated soil sampler demonstrate its suitability for collecting samples from predefined depths, particularly within the 0–30 cm arable layer, which is essential for agrochemical monitoring and the development of digital maps of soil indicators.

A separate block of contemporary research focuses on the impact of military activities on soil cover. Paulo Pereira, F. Bašić, I. Bogunovic, and D. Barcelo note that military activities may significantly alter the physical, chemical, and biological properties of soils, while explosions, mining activities, trench excavation, and military fortification works are capable of destroying soil horizons, mixing soil profiles, and causing land degradation [4]. N. O. Didenko, in her study on soil damage and restoration in Ukraine, emphasizes that warfare leads to soil degradation through contamination, destruction of agricultural lands, and disruption of natural ecosystems [5].

Despite the existing scientific achievements, the issue of hardware and technical support for the soil data acquisition process — as the primary stage of automated land assessment — remains insufficiently covered. Professional publications provide limited discussion of the methodological and practical aspects of applying automated soil sampling systems in comparison with traditional methods, especially within territories affected by military activities. Insufficient attention has also been devoted to the representativeness of automated sampling, the integration of results into GIS platforms, the development of spatial heterogeneity maps for agrochemical indicators, and the use of such data for the post-war restoration of soil fertility. These considerations determined the choice of the research direction.

Purpose and Objectives of the Study. The purpose of this study is to assess the ecological and agrochemical condition of an agricultural land plot affected by military activities based on the results of automated soil sampling performed using the Bodenprobenehmer N2006 system, laboratory analysis of agrochemical and ecological-toxicological indicators, and the determination of spatial heterogeneity of the soil cover.

To achieve the stated purpose, the following objectives were defined:

- to characterize the soil cover and land-use conditions of the investigated agricultural land plot;
- to conduct automated soil sampling with subdivision of the territory into elementary sampling units;
- to determine the main agrochemical soil indicators, including pH, humus content, easily hydrolyzable nitrogen, and mobile phosphorus and potassium compounds;
- to assess the content of mobile forms of micronutrients and heavy metals;
- to identify the spatial heterogeneity of soil indicators using statistical data processing methods;
- to establish potential signs of military impact on the ecological and agrochemical condition of soils and to substantiate directions for further monitoring and soil fertility restoration.

Materials and Methods of the Study. The research was conducted in accordance with Agreement No. DZ/168-2025 dated February 12, 2025, concluded between the State Institution Institute for Soil Protection of Ukraine and the Ministry of Education and Science of Ukraine entitled “Investigation of the Agrochemical Condition and the Impact of Military Activities on Agricultural Lands to Ensure Sustainable Agricultural Production.”

The object of the study was an agricultural land plot with an area of 279.4175 hectares, located outside the village of Bryhadyrivka within the Izium Territorial Community of Izium Raion, Ukraine.

To assess the ecological and agrochemical condition of the soil cover, 60 composite soil samples were collected using the automated Bodenprobenehmer N2006 soil sampling system.

During the period from March to September 2022, the specified land plot was subjected to military impact as a result of active hostilities. During this period, the land was not used for agricultural production, and its economic utilization was resumed only in the spring of 2024. According to the land user's testimony, following the withdrawal of military units, a system of trenches and dugouts up to 3 m in length and approximately 1.5 m in depth, traces of fires, and signs of soil compaction caused by the movement of heavy military machinery were identified within the study area.

The soil cover of the investigated land plot is represented by the following soil types: ordinary slightly eroded heavy loamy and light clayey chernozems (agro-production group 65e) — the dominant soil type; ordinary medium-humus deep heavy loamy and light clayey chernozems (agro-production group 58e, classified as especially valuable soils of the Left-Bank Steppe Province) [18]; medium- and strongly solonetzic chernozems developed on dense clays, slightly eroded heavy loamy soils (agro-production group 89e); as well as eroded heavy loamy and light clayey soils and deposits of loose loess-like parent materials (agro-production group 215e).

Agro-production groups 65e and 89e belong to the chernozem soil category; however, they differ in the degree of degradation and erosion, which significantly affects their natural fertility and agricultural productivity. Soils of agro-production group 65e are characterized by moderate productivity, whereas soils of groups 89e and 215e demonstrate lower productivity and require the implementation of agrotechnical measures aimed at improving the water regime, enhancing soil structure formation, and, where necessary, applying deep tillage practices.

For mechanized soil sampling, a mobile automated Bodenprobenehmer N2006 complex manufactured by Bodenprobetechnik Peters GmbH was used. The system was mounted on a high-mobility pickup-type vehicle. The complex is equipped with an automatic soil sampler, a navigation system, a field computer, and a GPS/RTK receiver. The equipment provides automated soil sampling from the arable layer at a depth of 0–30 cm using a predefined grid interval and recording sampling locations by means of GPS coordinates. During field operations, the field boundary was delineated using the specialized Field-Expert software, after which the field area was divided into elementary sampling units for representative soil sampling.

The land parcel was subdivided into 60 elementary plots, each with an area of up to 5 hectares, which ensured a higher spatial resolution compared with the standard density applied in agrochemical certification surveys. Within each elementary plot, up to 30 point soil samples were collected using the automated sampler, from which one composite sample was formed (Fig. 1).

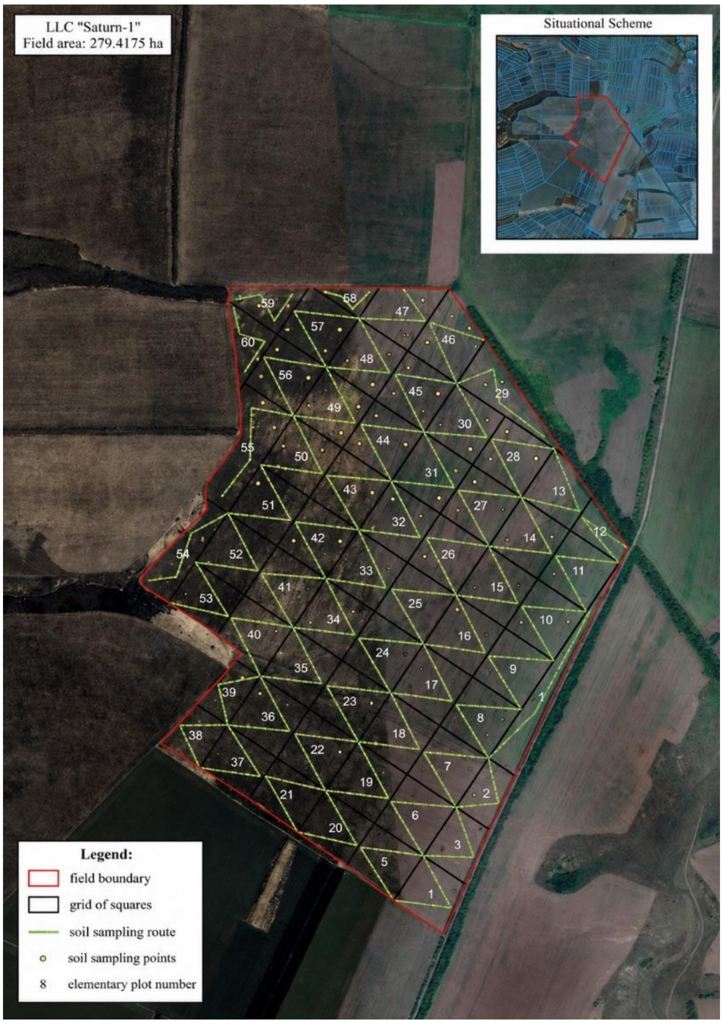

Fig. 1. Arrangement of elementary plots within the study area (Bryhadyrivka village, Izium Territorial Community, Izium Raion, Kharkiv Oblast).

The main technical characteristics of the system are as follows: productivity — up to 100–120 hectares per working shift; sampling depth — 0–30 cm, adjustable; probe diameter — 20 mm; GPS navigation accuracy using an RTK receiver — ±0.3–

0.5 m; automatic labeling of samples with GPS coordinates; and container capacity — 100–200 samples per loading cycle. The system can be integrated with agricultural GIS platforms, enabling the automated generation of digital maps of agrochemical soil indicators for further application in precision agriculture systems and variable-rate fertilizer application technologies [10, 11].

The application of the automated Bodenprobenehmer N2006 system provides several advantages compared with traditional manual soil sampling methods. In particular, automated sampling ensures higher fieldwork productivity, precise GPS georeferencing of sampling locations, reduction of human-factor influence, standardization of sampling depth and the number of point samples, as well as the possibility of subsequent integration of results into GIS platforms. This is especially important when surveying large land areas and territories affected by military activities, where high spatial resolution and enhanced safety of field operations are required. A comparative characteristic of traditional and automated soil sampling methods is presented in Table 1.

Table 1. Comparative Characteristics of Traditional and Automated Soil Sampling Methods

Criterion	Traditional Sampling	Automated Sampling
Sampling method	Manual sampling using an auger, probe, or shovel	Mechanized sampling using an automatic soil sampler
Productivity	Lower; depends on the number of workers and field conditions (manual labor)	Higher; up to 100–120 ha per shift
Sampling depth	May vary depending on the operator	Standardized, adjustable depth of 0–30 cm
GPS georeferencing	Often manual or selective	Automated recording of sampling point coordinates
Human factor	High influence of the operator on sampling uniformity and accuracy	Human-factor influence minimized
Representativeness	Depends on the operator's experience and compliance with methodology	Ensured through a predefined grid, number of sampling points, and GPS navigation
Work safety	Lower on military-affected sites	Higher due to mechanization and

	due to prolonged personnel presence in the field	reduced duration of field operations
GIS integration	Requires additional data transfer and processing	Direct integration with digital maps and GIS platforms is possible
Application in precision agriculture	Limited without additional digital processing	Suitable for generating digital maps and variable-rate fertilizer application

Soil sampling was carried out in accordance with the requirements of DSTU 4287:2004 *"Soil Quality. Sampling"* [19]. Samples were collected from the arable layer at a depth of 0–30 cm, which is considered representative for the assessment of technogenic contamination, since this soil horizon is characterized by the accumulation of mobile forms of heavy metals and their direct interaction with plant root systems [9, 12, 20]. Laboratory analysis of the samples was performed in the accredited laboratory of the North-Eastern Interregional Center of the State Institution Derzhgruntookhorona.

The agrochemical soil indicators were determined in accordance with the following regulatory standards: soil solution reaction (pH) — DSTU 7862:2015 [21]; humus (organic matter) content — DSTU 4289:2004 [22]; content of easily hydrolyzable nitrogen — DSTU 7863:2015 [23]; and the content of mobile phosphorus and potassium compounds — DSTU 4115:2002 [24].

Ecological and toxicological indicators were determined in an ammonium-acetate buffer solution with pH 4.8 in accordance with the DSTU 4770:2007 series of standards. In particular, the content of mobile compounds of manganese was determined according to DSTU 4770.1:2007 [25], zinc — DSTU 4770.2:2007 [26], cadmium — DSTU 4770.3:2007 [27], iron — DSTU 4770.4:2007 [28], cobalt — DSTU 4770.5:2007 [29], copper — DSTU 4770.6:2007 [30], nickel — DSTU 4770.7:2007 [31], and lead — DSTU 4770.9:2007 [32].

The classification of soils according to agrochemical indicators was carried out in accordance with the *Methodology for Agrochemical Certification of Agricultural Lands* [20]. The assessment of the ecological and toxicological condition of soils based on the content of mobile heavy metal compounds, as well as the determination of land suitability for agricultural crop cultivation, was performed by comparing the measured concentrations with the maximum permissible concentrations (MPCs) established by current regulatory standards [33].

The boundaries of contaminated areas potentially affected by military activities [35] were determined by identifying elementary plots in which elevated concentrations of mobile forms of heavy metals were detected. This approach made it possible not only to determine the overall level of contamination, but also to localize individual hotspots of increased concentrations characteristic of soils damaged as a result of military impact.

Statistical processing of the experimental data was performed using the Microsoft Excel and Statistica 6.0 software packages. The principal descriptive statistical indicators were calculated, including mean value, minimum, maximum, standard error, standard deviation, and coefficient of variation. To assess sample homogeneity and the reliability of the obtained mean values, the coefficient of variation (V, %) was determined, characterizing the degree of dispersion of individual indicators relative to the arithmetic mean. Variation was considered weak at $V \leq 5\%$, moderate at 6–10%, significant at 10–20%, high at 21–50%, and very high at $V > 50\%$.

The spatial heterogeneity of soil indicators was assessed through a combination of average values for the elementary plots, variation ranges, coefficients of variation, and the distribution structure of samples according to fertility or contamination levels. This approach enabled the identification of local hotspots with elevated agrochemical and toxicological indicator values and allowed assessment of the spatial distribution patterns of these indicators within the investigated land plot.

Results and Discussion. The results of the conducted research indicate that the soil of the investigated land plot generally exhibits a nearly neutral soil solution reaction. The weighted average pH value was 5.8, while within the elementary plots the indicator varied from 5.6 to 6.0 pH units. All 60 samples were characterized by a nearly neutral soil reaction. The coefficient of variation was 2%, indicating weak variation and a high degree of homogeneity of the indicator. Based on the obtained results, no direct impact of military activities on soil acidity was identified. The stability of the pH indicator may indicate the high buffering capacity of chernozem soils, which likely limited the manifestation of possible chemical effects caused by explosion and combustion products on the soil solution reaction [5, 34].

The soil cover of the investigated area is characterized by a high humus content. The weighted average value amounted to 4.13%, whereas within the elementary plots the humus content varied from 3.15 to 4.81%. Of the 60 samples analyzed, 39 were characterized by high humus content ranging from 4.16 to 4.81%, while 21 samples demonstrated elevated humus content within the range of 3.15–3.92%. The coefficient of variation was 9.2%, indicating moderate variation of the indicator.

The identified differences may be attributed to natural soil-forming processes, the mosaic structure of the soil cover, and local variations in organic matter accumulation. According to the laboratory analysis results, no direct impact of military activities on the total humus content was detected. At the same time, locally disturbed areas, particularly locations affected by trench and dugout excavation, may experience physical mixing of genetic horizons, destruction of the soil profile structure, and localized decreases in soil fertility, which is consistent with findings regarding the mechanical degradation of soils resulting from military activities [4, 5, 10, 11].

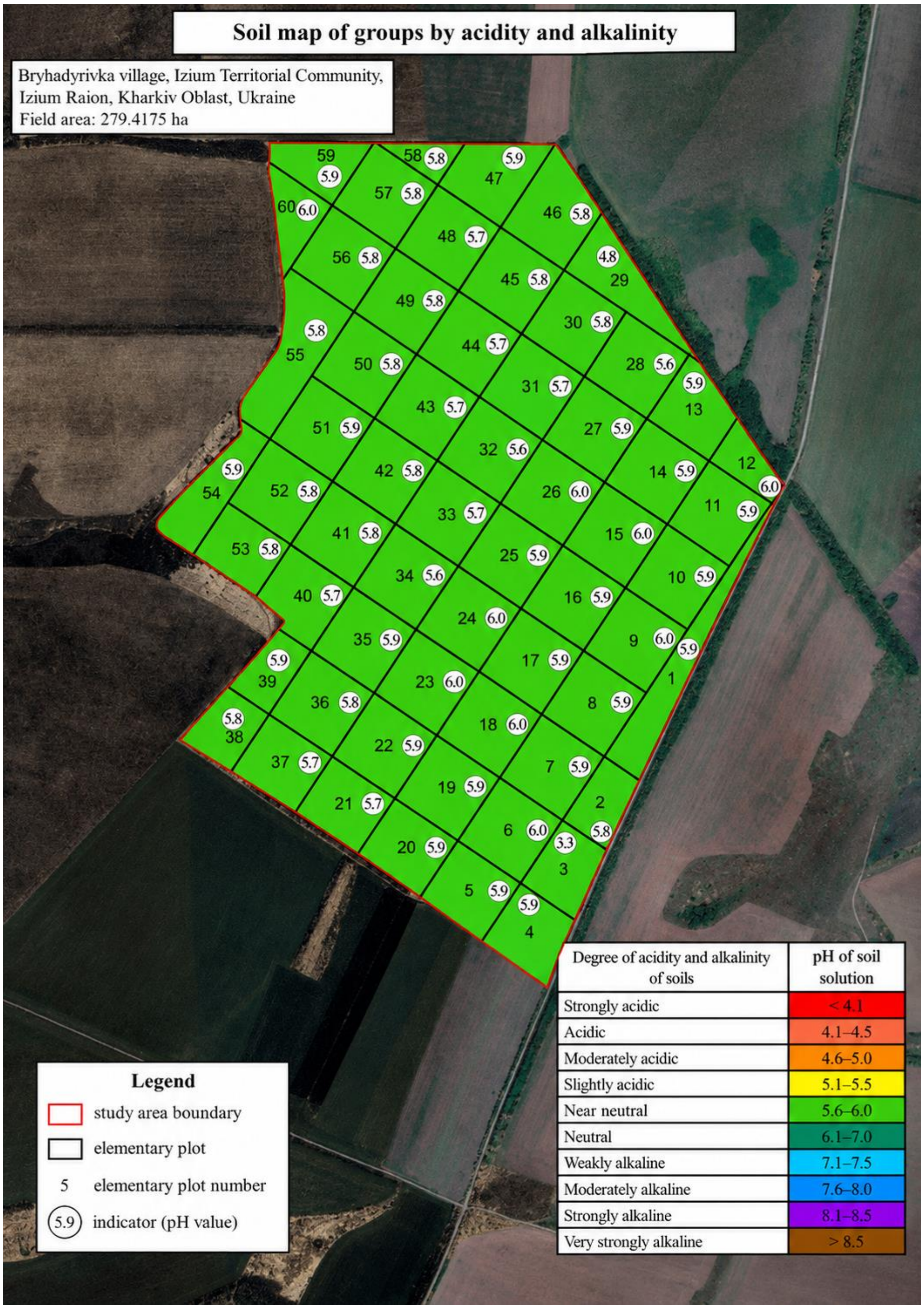

Fig. 2. Cartogram of the soil solution reaction (pH) of the investigated land plot.

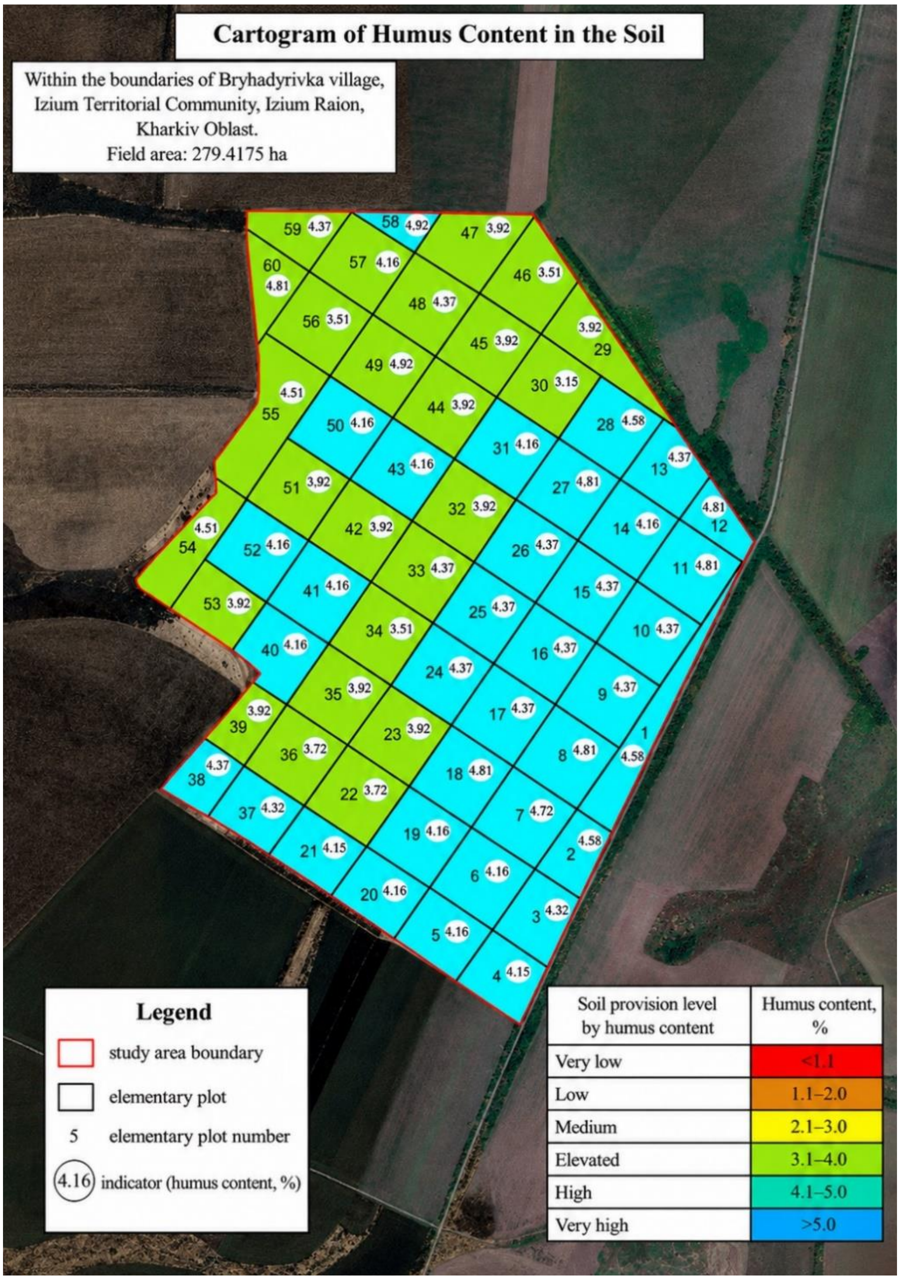

Fig. 3. Cartogram of the spatial distribution of humus (organic matter) content in the soils of the investigated land plot.

According to the content of mobile phosphorus compounds, the soil of the investigated land plot is generally characterized by a medium level of phosphorus supply (Fig. 5). The weighted average value amounted to 86 mg/kg of soil, while the indicator varied from 70 to 145 mg/kg. In particular, 56 out of 60 samples demonstrated a medium level of phosphorus supply within the range of 70–94 mg/kg, whereas 4 samples were characterized by an elevated level ranging from 102 to 145 mg/kg. The coefficient of variation was 13.1%, indicating significant variability of the indicator.

The impact of military activities on the content of mobile phosphorus compounds may be localized and indirect in nature, particularly due to the input of combustion products from plant residues or other materials into the soil.

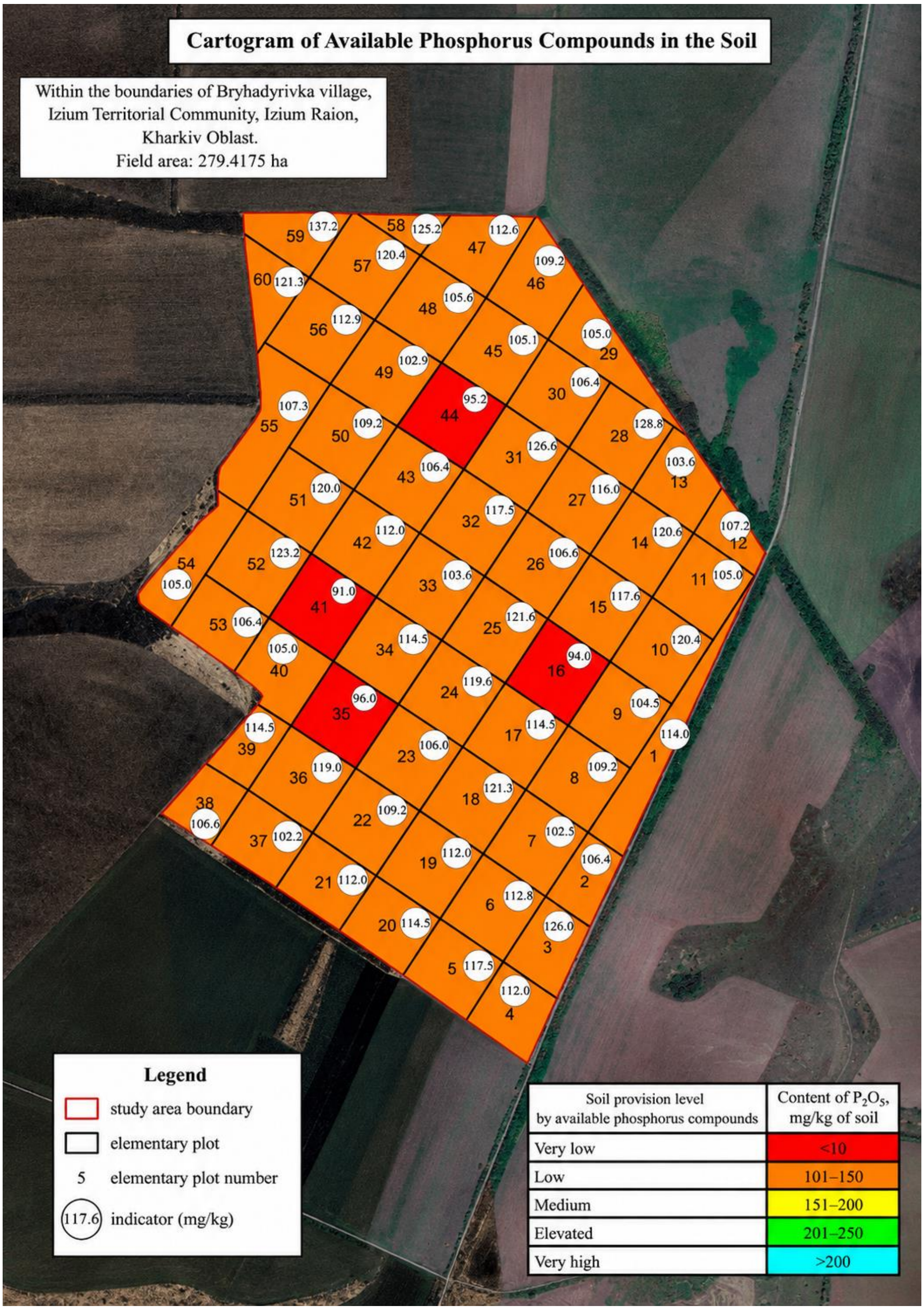

Figure 4. Cartogram of the Spatial Distribution of Easily Hydrolyzable Nitrogen Content in the Soils of the Investigated Land Plot

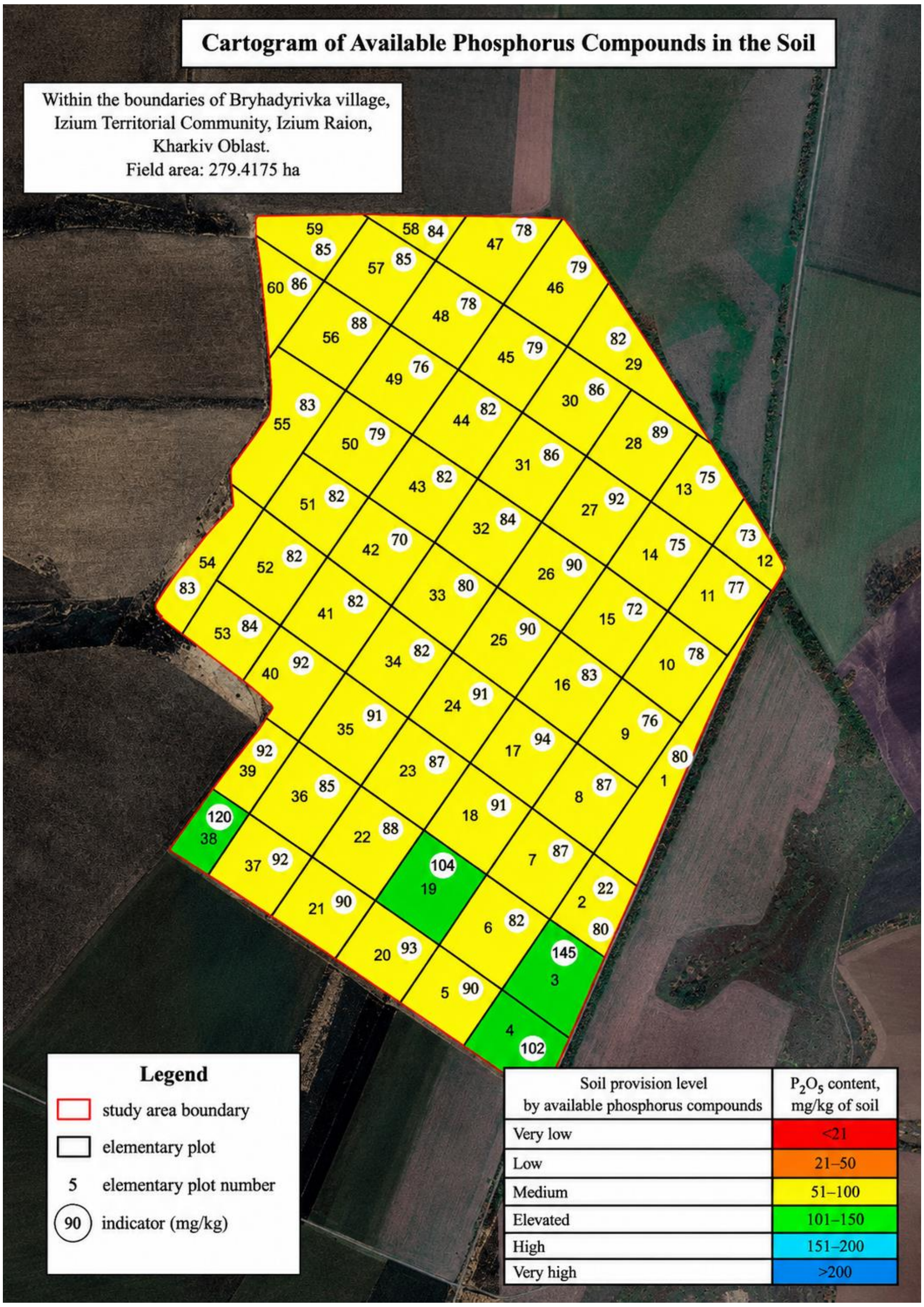

Figure 5. **Cartogram of the Spatial Distribution of Mobile Phosphorus Compounds Content in the Soils of the Investigated Land Plot**

The soil supply with mobile potassium compounds was assessed as high (Fig. 6). The weighted average value was 145 mg/kg of soil, while the parameter varied from 113 to 192 mg/kg. In particular, 49 out of 60 samples exhibited a high level of potassium supply within the range of 121–179 mg/kg, 6 samples showed a very high level within 182–192 mg/kg, and 5 samples demonstrated an increased level within 113–118 mg/kg. The coefficient of variation amounted to 14.5%, indicating considerable variability of the parameter. Such heterogeneity may partly be associated with the consequences of fires and explosions, as combustion products and ash can serve as additional sources of potassium in soil.

The soil cover of the investigated area was characterized by a low content of mobile manganese compounds (Fig. 7). The weighted average value was 6.48 mg/kg of soil, while within the elementary plots the parameter ranged from 2.41 to 13.81 mg/kg. Of the 60 samples, 34 showed a low manganese content within 5.05–6.99 mg/kg, 15 samples had a medium content within 7.05–9.13 mg/kg, 9 samples demonstrated a very low content within 2.41–4.82 mg/kg, and two samples exhibited an increased content within 10.08–13.81 mg/kg. The coefficient of variation reached 27.1%, indicating high variability and spatial heterogeneity of manganese distribution. The identified differences may be attributed both to the natural mosaic structure of the soil cover and to the local impact of military activities, which contributed to the redistribution of micronutrients within the upper soil layer.

The soil supply with mobile zinc compounds was assessed as very low (Fig. 8). The weighted average value amounted to 0.44 mg/kg, varying from 0.32 to 0.93 mg/kg of soil. All samples were characterized by zinc deficiency, which may adversely affect crop productivity, reduce plant resistance to stress factors, and deteriorate the quality characteristics of yield. The coefficient of variation was 19.7%, indicating significant variability of the parameter. The impact of military activities on the content of mobile zinc compounds was not clearly observed, since zinc deficiency may have a regional or soil-geochemical origin.

According to the content of mobile copper compounds, the soil was characterized by an increased level of supply (Fig. 7). The weighted average value amounted to 0.21 mg/kg of soil, while the parameter varied from 0.15 to 0.34 mg/kg. In particular, 29 out of 60 samples had a medium copper content within 0.16–0.20 mg/kg, 27 samples demonstrated an increased content within 0.21–0.30 mg/kg, 3 samples showed a low content at the level of 0.15 mg/kg, and one sample exhibited a high content of 0.34 mg/kg.

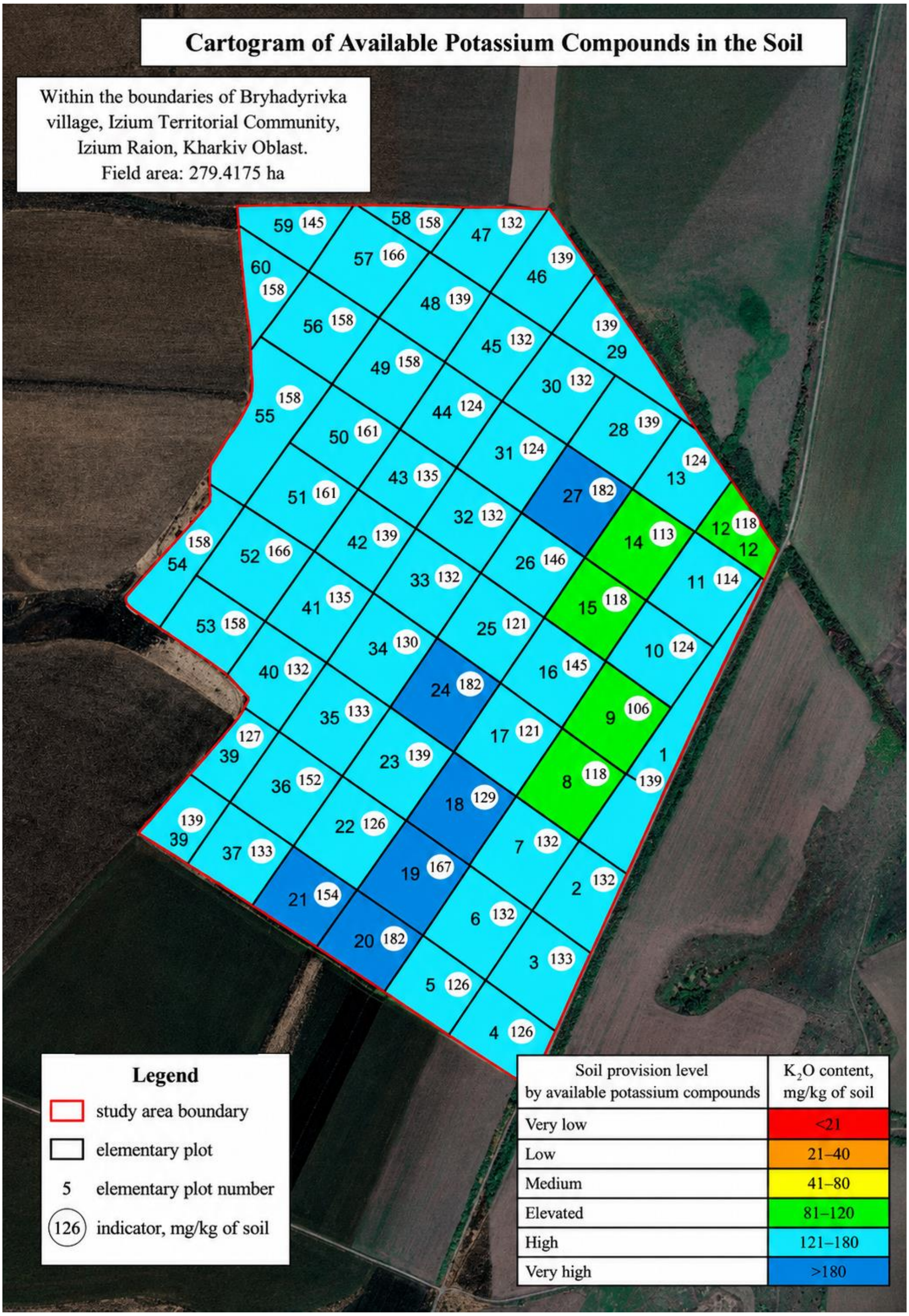

Figure 6. Cartogram of the Spatial Distribution of Mobile Potassium Compounds Content in the Soils of the Investigated Land Plot

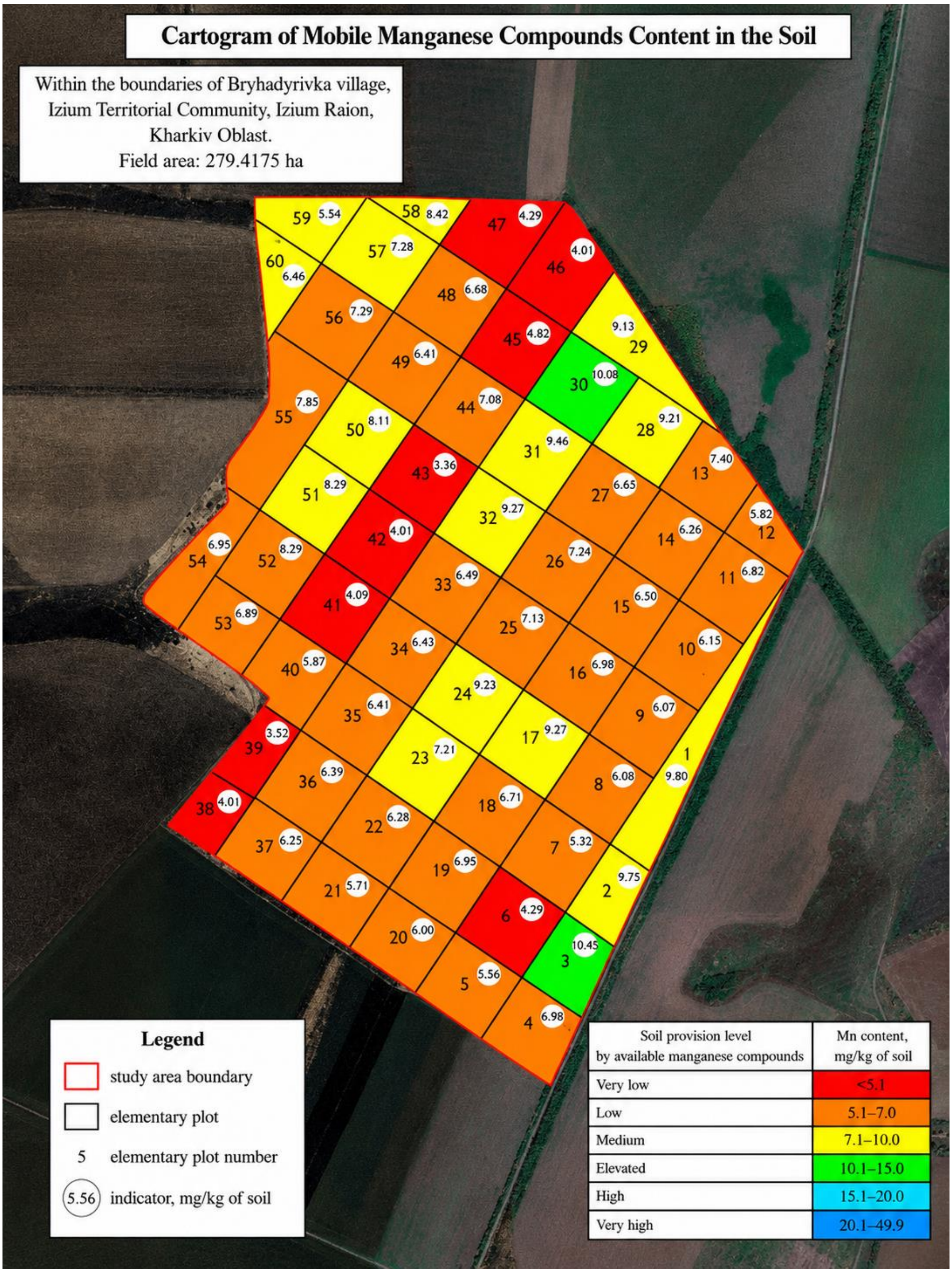

Figure 7. Cartogram of the Spatial Distribution of Mobile Manganese Compounds Content in the Soils of the Investigated Land Plot

The coefficient of variation amounted to 18.2%, indicating considerable variability of the parameter. Local fluctuations in copper content may be associated both with the natural heterogeneity of the soil cover and with the consequences of explosions and fires, which are capable of influencing the redistribution of metals within the upper soil layer.

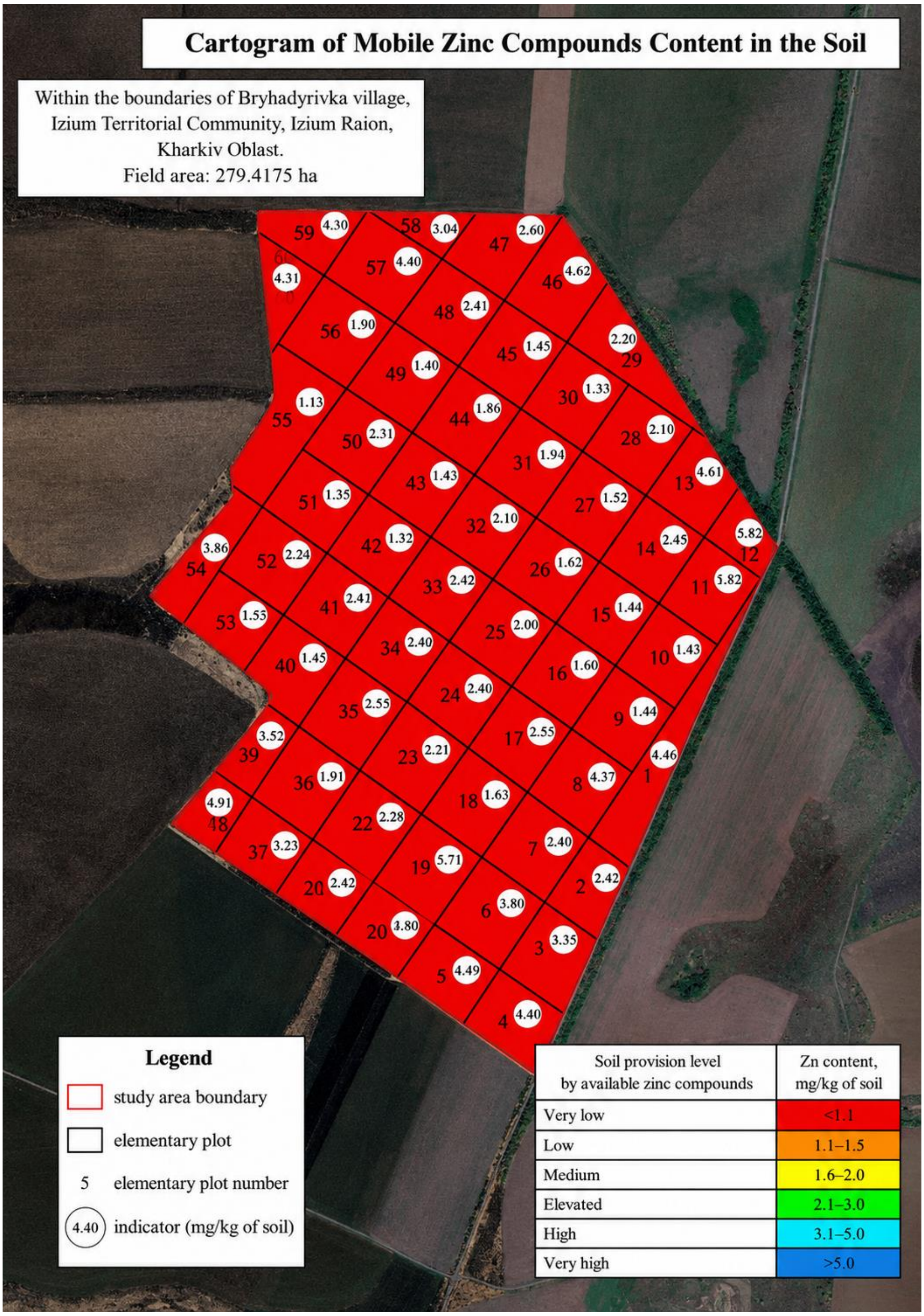

Figure 8. Cartogram of the Spatial Distribution of Mobile Zinc Compounds Content in the Soils of the Investigated Land Plot

Figure 9. Cartogram of the Spatial Distribution of Mobile Copper Compounds Content in the Soils of the Investigated Land Plot

The weighted average content of mobile iron compounds within the investigated area amounted to 13.84 mg/kg of soil, varying from 2.05 to 30.9 mg/kg. The coefficient of variation reached 48.7%, indicating high variability and substantial spatial heterogeneity of the parameter. Such fluctuations may be attributed to natural differences in soil texture, organic matter content, and redox conditions. At the same time, the local impact of military activities cannot be excluded, particularly due to the input of corrosion products from military equipment, metallic fragments, and residues of explosive materials. Overall, the spatial distribution of iron exhibited a mosaic pattern.

According to the content of mobile cobalt compounds, the soil was characterized by a very high level of supply. The weighted average value amounted to 0.41 mg/kg of soil, with variation ranging from 0.23 to 0.71 mg/kg. Of the 60 samples, 48 exhibited a very high cobalt content within 0.31–0.49 mg/kg, 6 samples showed a high content within 0.23–0.30 mg/kg, while in another 6 samples a slight level of contamination was recorded within 0.54–0.71 mg/kg. It should be noted that in 10 samples the cobalt content was close to the threshold of slight contamination, ranging from 0.45 to 0.49 mg/kg. The coefficient of variation amounted to 21.7%, indicating considerable variability of the parameter. Elevated cobalt concentrations at certain sampling points may be associated with the local deposition of explosion-derived products or metallic particles.

According to the content of mobile nickel compounds, the soil was characterized by a slight level of contamination. The weighted average value amounted to 2.56 mg/kg of soil, varying from 1.44 to 3.49 mg/kg. In particular, 50 out of 60 samples demonstrated a slight level of nickel contamination within 2.08–3.49 mg/kg, whereas in 10 samples the nickel content corresponded to background values ranging from 1.44 to 1.92 mg/kg. No exceedance of the maximum permissible concentration was recorded. The coefficient of variation amounted to 20.0%, corresponding to significant variability and indicating moderate spatial heterogeneity of the parameter distribution. The impact of military activities on the content of mobile nickel compounds in soil was assessed as insignificant.

The weighted average content of mobile cadmium compounds amounted to 0.16 mg/kg of soil, while the parameter varied from 0.09 to 0.23 mg/kg. Among the individual samples, 42 out of 60 were characterized by a slight level of cadmium contamination within 0.10–0.19 mg/kg, 15 samples exhibited a moderate level of contamination within 0.20–0.23 mg/kg, and 3 samples were at the contamination threshold with a content of 0.09 mg/kg. The total area contaminated with cadmium amounted to 266.4609 ha, corresponding to 95.4% of the investigated area. Of this, a moderate level of contamination was recorded over 70.1712 ha (25.15%), while a slight level of contamination covered 196.2897 ha (70.25%). No contamination by mobile cadmium compounds was detected within an area of 12.9565 ha, accounting for 4.6% of the investigated territory. The coefficient of variation amounted to 25.3%, indicating high variability and the presence of local hotspots with elevated cadmium concentrations. Such variability may be associated with the influence of local anthropogenic factors, particularly the consequences of military activities, including the introduction of metallic fragments, vehicle particles, or explosive residues into the soil, which may serve as sources of heavy metals.

According to the content of mobile lead compounds, the soil was characterized by a slight level of contamination. The weighted average value amounted to 1.18 mg/kg of soil, while the parameter ranged from 0.81 to 1.67 mg/kg. Of the 60 samples, 50 exhibited a slight level of lead contamination within 0.81–1.44 mg/kg, whereas 10 samples demonstrated a moderate level of contamination within 1.47–1.67 mg/kg. The coefficient of variation amounted to 18.9%, indicating considerable variability of the parameter. Elevated lead concentrations in individual samples may be associated with the consequences of military activities, since lead is one of the characteristic components of military-technogenic soil contamination.

In addition to changes in chemical composition, physical degradation of the soil cover represents an important factor contributing to the deterioration of the investigated area. The presence of trenches and dugouts up to 1.5 m deep indicates local disturbance of the soil profile structure and possible displacement of low-fertility subsoil horizons to the surface. The movement of heavy military equipment may have caused excessive compaction of both the plough and subplough layers, adversely affecting the soil water, air, and thermal regimes. An additional limiting factor is technogenic contamination of the territory with metallic and plastic debris, which complicates field operations and necessitates preliminary site clearance.

Conclusions and Prospects for Further Research. The results of the study demonstrated that the investigated land plot, with an area of 279.4175 ha, is characterized by a nearly neutral soil reaction, high humus content, and a generally preserved potential of natural soil fertility. At the same time, an imbalance in certain agrochemical indicators was identified, including low availability of easily hydrolyzable nitrogen, a medium level of supply with mobile phosphorus compounds, and a high level of supply with mobile potassium compounds. These findings indicate the necessity of adjusting the fertilization system with consideration of the spatial heterogeneity of the soil cover.

The ecological and toxicological assessment revealed the widespread occurrence of elevated concentrations of mobile cadmium compounds across 95.4% of the investigated area, as well as slight and moderate levels of lead contamination within individual elementary plots. The spatial heterogeneity of micronutrient and heavy metal distribution may be associated both with the natural mosaic structure of the soil cover and with localized military-technogenic impacts.

The application of the automated sampling complex *Bodenprobenehmer N2006* ensured representative soil sampling, GPS-based georeferencing of sampling points, and the possibility of generating spatially detailed maps of agrochemical and ecological-toxicological indicators. This confirms the feasibility of using automated systems for monitoring, land reclamation, and the implementation of precision agriculture technologies on lands affected by military activities.

Prospects for further research are associated with repeated monitoring of the investigated area, assessment of the dynamics of mobile heavy metal forms, analysis of their transfer into crop production, and evaluation of the effectiveness of reclamation measures.

References

1. Muzychenko-Kozlovska O. V., Danylovych T. B., Havryliak A. S., Dziurakh Yu. M. Analizuvannia diialnosti systemy monitorynhu stanu gruntiv v Ukraini [Analysis of the functioning of the soil condition monitoring system in Ukraine]. Naukovi zapysky Natsionalnoho universytetu “Ostrozka akademiia”. Seriia: Ekonomika [Scientific Notes of the National University “Ostroh Academy”. Series: Economics]. 2022. No. 25(53). P. 4–10. DOI: https://doi.org/10.25264/2311-5149-2022-25(53)-4-10.

2. Nahirniak S. V., Dontsova T. A., Lapinskyi A. V., Tereshkov M. V. Soil and soil breathing remote monitoring: A short review. Ecology and Noospherology. 2020. Available at: https://ecology.dp.ua/index.php/ECO/article/view/1063.

3. Chornyi S. O. Otsinka yakosti gruntiv [Assessment of soil quality] : navch. posib. [study guide]. Mykolaiv : MNAU, 2018. 233 p.

4. Pereira P., Bašić F., Bogunovic I., Barcelo D. Russian-Ukrainian war impacts the total environment. Science of The Total Environment. 2022. Vol. 837. Art. 155865. DOI: https://doi.org/10.1016/j.scitotenv.2022.155865.

5. Didenko N. O. Soil damage and recovery in Ukraine: lessons from global post-war experiences. Land Reclamation and Water Management. 2024. No. 2. P. 79–86. DOI: https://doi.org/10.31073/mivg202402-391.

6. Petruk Yu., Artiukh O. Innovatsiini pidkhody do zemlerobstva: avtomatyzatsiia i robotyzatsiia mashynno-traktornykh ahrehativ dlia optymizatsii vytrat ta zberezhennia gruntiv [Innovative approaches to agriculture: automation and robotization of machine-tractor units for cost optimization and soil conservation]. Suchasni tekhnolohii v mashynobuduvanni ta transporti [Modern Technologies in Mechanical Engineering and Transport]. 2023. No. 2. P. 112–118. Available at: https://eforum.lntu.edu.ua/index.php/jurnal-mbf/article/view/1741.

7. Fedasiuk D. V., Kostiuk M. O. Prohnozuvannia volohosti gruntu z vykorystanniam mashynnoho navchannia u systemakh rozumnoho zemlerobstva [Prediction of soil moisture using machine learning in smart farming systems]. Ukrainskyi zhurnal informatsiinykh tekhnolohii [Ukrainian Journal of Information Technology]. 2024. Vol. 6, No. 1. P. 26–36. DOI: https://doi.org/10.23939/ujit2024.01.026.

8. Kammerlander C., Kolb V., Luegmair M., Scheermann L., Schmailzl M., Seufert M., Zhang J., Dalic D., Schön T. Machine Learning Models for Soil Parameter Prediction Based on Satellite, Weather, Clay and Yield Data. arXiv. 2025. DOI: https://doi.org/10.48550/arXiv.2503.22276.

9. Metodyka provedennia ahrokhimichnoho obstezhennia gruntiv iz zastosuvanniam mekhanizovanykh probovidbirnykiv [Methodology for agrochemical soil survey using mechanized samplers]. Kyiv : NTTs “Ahrokhimservis”, 2024. Available at: https://agrohim.gov.ua/methods/sampling.

10.Gruntovidbirnyk Nietfeld N2006 — avtomatyzovana systema vidboru zrazkiv gruntu [Nietfeld N2006 soil sampler — automated soil sampling system]. AgroGeo. Available at: https://www.agrogeo.com.ua/catalog/nietfeld-n2006-2.

11.Bodenprobenehmer N2006 – Soil sampling system. Bodenprobetechnik Peters GmbH. Available at: https://www.bodenprobetechnik.de/en/bodenprobenehmer-n2006.

12.Udovenko I. O. Yakisne otsiniuvannia zemelnykh resursiv z metoiu vyznachennia tsinnosti pryrodnykh resursiv [Qualitative assessment of land resources for determining the value of natural resources] // Ekolohichno bezpechne, vysokoproduktyvne vykorystannia gruntu ta zastosuvannia dobryv : zb. tez Vseukr. nauk.-prakt. konf. (m. Uman, 29 berez. 2017 r.) [Environmentally safe, highly productive soil use and fertilizer application: Conference proceedings]. Uman, 2017. P. 109–110. Available at: http://lib.udau.edu.ua/handle/123456789/6323.

13.Cherlinka V. R., Zaharovskyy V. S. Directions of automatization for calculation of soil qualitative assessment. AgroChemistry and Soil Science. 2016. Vol. 85. P. 40–46. DOI: https://doi.org/10.31073/acss85-06.

14.McBratney A., Whelan B., Ancev T., Bouma J. Future Directions of Precision Agriculture. Precision Agriculture. 2005. Vol. 6. P. 7–23. DOI: https://doi.org/10.1007/s11119-005-0681-8.

15.Farmaha B. S., Caughman W., Park D. Precision Agriculture-Based Soil Sampling Strategies. Clemson Cooperative Extension. Available at: https://lgpress.clemson.edu/publication/precision-agriculture-based-soil-sampling-strategies.

16.Gonçalves J. R. M. R., Ferraz G. A. e S., Reynaldo É. F., Marin D. B., Ferraz P. F. P., Pérez-Ruiz M., Rossi G., Vieri M., Sarri D. Comparative analysis of soil-sampling methods used in precision agriculture. Journal of Agricultural Engineering. 2021. Vol. 52, No. 1. DOI: https://doi.org/10.4081/jae.2021.1117.

17.Adamchuk V. I., Hummel J. W., Morgan M. T., Upadhyaya S. K. On-the-go soil sensors for precision agriculture. Computers and Electronics in Agriculture. 2004. Vol. 44. P. 71–91. DOI: https://doi.org/10.1016/j.compag.2004.03.002.

18.Pro zatverdzhennia pereliku osoblyvo tsinnykh hrup gruntiv [On approval of the list of especially valuable soil groups] : nakaz Derzhavnoho komitetu Ukrainy po zemelnykh resursakh vid 06.10.2003 No. 245. Available at: https://zakon.rada.gov.ua/go/z0979-03.

19.DSTU 4287:2004. Yakist gruntu. Vidbyrannia prob [Soil quality. Sampling]. Kyiv : Derzhspozhyvstandart Ukrainy, 2005. 6 p.

20.Metodyka provedennia ahrokhimichnoi pasportyzatsii zemel silskohospodarskoho pryznachennia [Methodology of agrochemical certification of agricultural lands] / za red. I. P. Yatsuka, S. A. Baliuka. 2nd ed. Kyiv, 2019. 108 p.

21.DSTU 7862:2015. Yakist gruntu. Vyznachennia aktyvnoi kyslotnosti [Soil quality. Determination of active acidity]. Kyiv : Derzhspozhyvstandart Ukrainy, 2015. 13 p.

22.DSTU 4289:2004. Yakist gruntu. Metody vyznachannia orhanichnoi rechovyny [Soil quality. Methods for determination of organic matter]. Kyiv : Derzhspozhyvstandart Ukrainy, 2005. 14 p.

23.DSTU 7863:2015. Yakist gruntu. Vyznachennia lehkohidroliznoho azotu metodom Kornfilda [Soil quality. Determination of easily hydrolyzed nitrogen by Cornfield method]. Kyiv, 2015. 9 p.

24.DSTU 4115-2002. Grunty. Vyznachannia rukhomykh spoluk fosforu i kaliiu za modyfikovanym metodom Chyrykova [Soils. Determination of mobile phosphorus and potassium compounds by modified Chirikov method]. Kyiv, 2002. 10 p.

25.DSTU 4770.1:2007. Yakist gruntu. Vyznachennia vmistu rukhomykh spoluk marhantsiu... Kyiv, 2009. 14 p.

26.DSTU 4770.2:2007. Yakist gruntu. Vyznachennia vmistu rukhomykh spoluk tsynku... Kyiv, 2009. 14 p.

27.DSTU 4770.3:2007. Yakist gruntu. Vyznachennia vmistu rukhomykh spoluk kadmiiu... Kyiv, 2009. 14 p.

28.DSTU 4770.4:2007. Yakist gruntu. Vyznachennia vmistu rukhomykh spoluk zaliza... Kyiv, 2009. 14 p.

29.DSTU 4770.5:2007. Yakist gruntu. Vyznachennia vmistu rukhomykh spoluk kobaltu... Kyiv, 2009. 14 p.

30.DSTU 4770.6:2007. Yakist gruntu. Vyznachennia vmistu rukhomykh spoluk midi... Kyiv, 2008. 4 p.

31.DSTU 4770.7:2007. Yakist gruntu. Vyznachennia vmistu rukhomykh spoluk nikeliu... Kyiv, 2009. 14 p.

32.DSTU 4770.9:2007. Yakist gruntu. Vyznachennia vmistu rukhomykh spoluk svyntsiu... Kyiv, 2009. 14 p.

33.Pro zatverdzhennia normatyviv hranychno dopustymykh kontsentratsii nebezpechnykh rechovyn u gruntakh, a takozh pereliku takykh rechovyn [On approval of maximum permissible concentrations of hazardous substances in soils and their list] : postanova Kabinetu Ministriv Ukrainy vid 15.12.2021 No. 1325. Ofitsiinyi visnyk Ukrainy [Official Bulletin of Ukraine]. 2021. No. 99. Art. 6482. Available at: https://zakon.rada.gov.ua/go/1325-2021-%D0%BF.

34.Ozhovan O. O., Mikhaylyuk V. I. Soil acid-base buffering in the step agriculture lands. Ukrainian Journal of Ecology. 2019. Vol. 9, No. 3. P. 259–266. Available at: https://www.ujecology.com/articles/soil-acidbase-buffering-in-the-step-agriculture-lands.pdf.

35.Ibatullin S., Dorosh I., Dorosh O., Sakal O., Butenko Y., Kharytonenko R., Shtohryn H. Determination of economic losses on agricultural lands in connection with hostilities on the example of the territory of Kyivska oblast in Ukraine. Acta Scientiarum Polonorum. Formatio Circumiectus. 2022. Vol. 21, No. 2. P. 49–61. DOI: https://doi.org/10.15576/ASP.FC/2022.21.2.49.

О.М. Грищенко, Є.В. Бутенко, В.О. Грищенко, В.С. Божок, Д.В. Винник

ОЦІНКА ЕКОЛОГО-АГРОХІМІЧНОГО СТАНУ ЗЕМЕЛЬ СІЛЬСЬКОГОСПОДАРСЬКОГО ПРИЗНАЧЕННЯ НА ОСНОВІ АВТОМАТИЗОВАНОГО ВІДБОРУ ҐРУНТОВИХ ЗРАЗКІВ

Анотація. *У статті здійснено оцінку еколого-агрохімічного стану земель сільськогосподарського призначення із застосуванням автоматизованого комплексу відбору проб ґрунту Bodenprobenehmer N2006. Обґрунтовано*

актуальність використання автоматизованих технологій ґрунтового моніторингу в умовах інтенсифікації аграрного виробництва, розвитку точного землеробства та необхідності оцінювання земель, що зазнали воєнного впливу.

Дослідження проведено на земельній ділянці площею 279,4 га, розташованій за межами с. Бригадирівка Ізюмської ТГ Ізюмського району Харківської області. Для оцінювання стану ґрунтового покриву було відібрано 60 об'єднаних проб з орного шару 0–30 см із поділом території на елементарні ділянки площею до 5 га.

Проведено лабораторне визначення основних агрохімічних і еколого-токсикологічних показників ґрунту, зокрема реакції ґрунтового розчину, вмісту гумусу, легкогідролізованого азоту, рухомих сполук фосфору, калію, мікроелементів і важких металів. Статистичну обробку результатів виконано з визначенням середньозважених значень, меж варіювання та коефіцієнтів варіації.

Встановлено, що ґрунти досліджуваної ділянки характеризуються близькою до нейтральної реакцією ґрунтового розчину та високим вмістом гумусу, що свідчить про збереження природного потенціалу родючості. Водночас виявлено дисбаланс окремих агрохімічних показників, зокрема низьку забезпеченість легкогідролізованим азотом, дуже низький вміст рухомих сполук цинку та низький вміст марганцю. За результатами еколого-токсикологічного оцінювання встановлено поширення підвищеного вмісту рухомих сполук кадмію на значній частині досліджуваної площі, а також слабкий і помірний рівні забруднення свинцем в окремих елементарних ділянках.

Отримані результати свідчать про просторову неоднорідність агрохімічних і токсикологічних показників, що може бути пов'язано як із природною мозаїчністю ґрунтового покриву, так і з локальним воєнно-техногенним впливом. Обґрунтовано доцільність використання автоматизованих систем відбору проб для формування електронних карт ґрунтових показників, моніторингу забруднення, планування рекультиваційних заходів і впровадження елементів точного землеробства.

***Ключові слова**: ґрунт, еколого-агрохімічна оцінка, автоматизований відбір проб, Bodenprobenehmer N2006, агрохімічні показники, важкі метали, воєнний вплив, точне землеробство.*