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Electrophysical indicators of typical chernozems under the influence of combat actions and technological loading

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Abstract. The article presents the results of a study of the electrophysical indicators of typical chernozems that have been affected by combat actions and technological loading, as well as agrogenic use. The aim of the work was to identify changes in electrical conductivity, total mineralisation, salinity and the content of water-soluble calcium, sodium and potassium cation salts by comparing areas with different types of technogenic, agrogenic and post-agrogenic loading. According to the methodology, samples were taken from 0 to 40 cm at 10 cm intervals. Electrophysical parameters were measured in a water-soil paste (1:1) using an EZODO-8200 M conductometer and HORIBA LAQUAtwin ion meters. Additionally, correlations were established between electrical conductivity, total mineralisation, salinity and water-soluble salt content. Combat impact caused a decrease in electrical conductivity with depth, uneven distribution and accumulation of sodium and potassium salts in the upper layers. On the burnt fallow land, electrical conductivity decreased from 258 to 185 μS/cm and the potassium salt content from 55 to 7 ppm. In the road and equipment parking variants, an increase in electrical conductivity (up to 302 μS/cm) and accumulation of calcium salts up to 150 ppm and potassium up to 24 ppm were observed. In the arable land variant, electrical conductivity remained consistently high (up to 360 μS/cm), which was caused by agrogenic salt accumulation. On the ploughed section of the road, the indicators were moderate, indicating partial recovery. A strong correlation was found between electrical conductivity and calcium (+0.72) and sodium (+0.89), as well as a negative correlation with potassium (-0.35). The practical significance of the research results lies in the possibility of using electrical conductivity and water-soluble salt content as indicators of the degree of soil disturbance, which made it possible to quickly assess the degradation of agrogenic and technogenic disturbed areas of chernozems as a result of hostilities, as well as the possibility of formulating recommendations for the restoration of soil cover in the context of post-conflict land use

Keywords: military degradation; electrical conductivity; water-soluble salts; post-conflict land use; agrogenic use; fallow use

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INTRODUCTION

In the current conditions of military conflict and intense technogenic pressure on Ukraine's agricultural landscapes, the ability to quickly assess the state of the soil environment, in particular its physical and chemical properties, is becoming particularly relevant. Typical chernozems, as the most fertile soils intensively used in agriculture, are subject to the complex effects of military operations, including mechanical compaction from the passage of military equipment, thermal damage from fires, and chemical contamination from fuel and lubricants spilled on the surface. These factors alter the water regime, structural condition, biological activity, and thus the soil's ability to self-regenerate and self-clean. At the same time, agricultural use also changes the ionic composition of the soil solution, which complicates the diagnosis of the degree of soil degradation. Under these conditions, electrophysical indicators (electrical conductivity, total mineralisation, salinity), supplemented with information on the content of water-soluble calcium, sodium and potassium, can serve as indicators of edaphic disturbance, allowing for a rapid assessment of the level of degradation and the formulation of scientifically sound recommendations for soil cover restoration.

Operational monitoring of the agrobiological condition of agricultural land is an important component of modern agroecological control. One of the most effective methods of such control is the measurement of the electrical conductivity of the soil environment, which is a comprehensive indicator of its physical and chemical condition. According to data obtained by H.N. Kim & J.H. Park (2024), electrical conductivity is closely related to the content of nutrients in the soil, in particular such as nitrates, potassium and calcium, and also depends on moisture, organic matter content and soil particle size distribution. In their work, researchers R. Mustafa & A. Ansari (2024) confirmed the dependence of soil electrical conductivity on moisture, density, porosity and the degree of saturation with nutrients, which allows it to be used to predict the agrophysical condition and potential of the territory. Modern research pays particular attention to electrical conductivity as an indicator of the physicochemical state of the soil. Electrical conductivity can be used to indirectly assess a number of important properties, such as nutrient content, organic matter content, pH, etc. Studies by P. Mazur *et al.* (2022) have found that soil electrical conductivity has a strong positive correlation with potassium content (0.80) and a moderate correlation with magnesium content (0.48), confirming its high informative value for monitoring. The authors noted that electrical conductivity can be used as an indirect indicator of fertility and a basis for field zoning in precision farming systems. In addition, this indicator proved to be the most variable among all those studied, which indicates the sensitivity of electrical conductivity to spatial heterogeneity of the soil environment.

In studies by B. Prajuli *et al.* (2025), the physicochemical properties of soils in irrigated agroecosystems were characterised, where electrical conductivity proved to be a sensitive indicator of changes in nutrient content, organic matter and microbiological activity. The authors noted that maintaining electrical conductivity within optimal values is critical for preserving the biochemical balance of the soil and ensuring a stable yield under conditions of intensive irrigation. In the work of W. Mu *et al.* (2024), a method was proposed that allows the salinity of the soil to be assessed based on electrical conductivity and moisture content. The researchers conducted a series of field measurements in arid regions where traditional methods of salt determination are labour-intensive. They proved that electrical conductivity combined with moisture content can be an effective indicator of water-soluble salts. The authors emphasised that the developed method allows for the rapid identification of areas at risk of salinisation. In their work, scientists A. Lazaar *et al.* (2025) developed a model for rapid assessment of saturated extract conductivity using pedotransfer functions, FTIR spectroscopy, and machine learning. The work covered arid regions of North Africa, where traditional conductivity determination is difficult and expensive. The authors showed that the data obtained using these methods, combined with machine learning algorithms, allow for highly accurate prediction of the level of water-soluble salts in the soil. The conclusions of A. Lazaar *et al.* confirmed that electrical conductivity is a reliable indicator of salinisation, and its digital modelling opens up new opportunities for soil monitoring.

Due to military operations in Ukraine, thousands of hectares of fertile chernozems soil have been devastated by combat operations: explosions, fires, bombings, movement of military equipment across fields, etc. According to T. Chaika & I. Korotkova (2023), all this has caused physical, chemical, and biological disturbances to the soil cover. The main issue of concern is how different types of disturbances caused by combat operations affect soil parameters, plant succession, and its potential for recovery. Despite the considerable attention paid by scientists to electrical conductivity as one of the indicators of the physical and chemical state of the soil, the analysed works mainly focused on agronomic aspects, in particular the relationship between electrical conductivity and nutrient content, organic matter content, moisture and granulometric composition of the soil. At the same time, the impact of military operations and technogenic load on the electrophysical indicators of chernozems has not been sufficiently studied. The nature of the vertical distribution of water-soluble calcium, sodium and potassium cations in soil profiles that have undergone pyrogenic, mechanical and chemical influences, as well as their relationship with electrical conductivity indicators, remains poorly studied.

It is precisely the aspects of the impact of military operations on the electrical conductivity, total mineralisation and salinity of typical chernozems, along with studies of the characteristics of the accumulation of water-soluble salts in various types of disturbed areas, that remain insufficiently covered in the current scientific literature. This necessitated this study, which was aimed at a comprehensive assessment of the electrophysical indicators of typical chernozems under the influence of military degradation and technogenic load compared to natural areas, with the subsequent formation of scientifically based recommendations for their restoration. The aim of the study was to identify changes in the electrophysical indicators of typical chernozems (in particular, electrical conductivity, total mineralisation, salinity) and the content of water-soluble cation salts (calcium, sodium and potassium) under the influence of hostilities, by comparing areas with different types of technogenic, agrogenic and post-agrogenic loads, for further assessment of the degree of soil environment disturbance and determination of its restoration potential.

MATERIALS AND METHODS

The study involved the analysis of electrophysical parameters (electrical conductivity, total mineralisation, and salinity) of typical chernozems across two control variants, representing agrochemical and post-agrochemical influences, located at the Educational-Scientific-Production Centre "Dokuchaev Experimental Field" of the State Biotechnological University, as well as four variants subject to technogenic impact, situated near a research station in Kharkiv region, representing different conditions of military activity. The research was conducted during 2025 as part of the scientific project "Impact of Military Actions on the Soil Cover and Soil Quality in Ukraine" (State Registration No. 0124U005030). Field and laboratory investigations encompassed representative plots with varying degrees of disturbance, enabling comparative analysis of vertical distribution of parameters within the soil profile.

The first variant (burnt fallow) represented a fallow plot partially affected by pyrogenic degradation due to the burning of vegetation during military activities. The second variant (natural fallow) was a fallow plot with a natural grass cover that had developed over more than 70 years (absolute control). The third variant (compacted road) included a road constructed across arable land, repeatedly subjected to mechanical stress from the movement of military vehicles. The fourth variant (ploughed road) represented a ploughed section of a road, simulating the aftereffects of technogenic impact caused by vehicle movement. The fifth variant (arable land) consisted of a plot under continuous agrochemical use for over 100 years, without any military impact (control). The sixth variant (equipment parking area) included an area used for temporary stationing of military equipment, with potential contamination of the surface soil layer by fuel and lubricants. Soil samples for analysis were collected using an auger in layers of 0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm. These layers were chosen due to their agronomic significance, as the upper humus-accumulative horizon of typical chernozems experiences the greatest load. Samples were collected in triplicate to ensure statistical reliability of the data.

To standardise measurement conditions for electrophysical parameters, a 1:1 water-to-soil paste was prepared. This ratio minimises the variability of soil moisture under field conditions, ensures comparability between variants, and provides representative data on the ionic composition of the soil solution. Measurements of electrical conductivity, total mineralisation, and salinity were performed using an EZODO-8200 M conductometer-salimeter (manufacturer: Taiwan). The conductometric method allows rapid and accurate determination of the total ion content in the soil solution and was selected for its high sensitivity to changes in salt composition during operational monitoring of soil degradation processes. The content of water-soluble cationic salts of calcium, sodium, and potassium was determined using portable HORIBA LAQUAtwin ion meters (manufacturer: Japan). The ionometric method complements the conductometric approach and enables qualitative assessment of salt composition. Pairwise correlation analysis was applied to establish relationships between electrical conductivity and the content of water-soluble salts. Statistical processing, graph construction, and result summarisation were conducted using Microsoft Excel (Microsoft 365 Education), ensuring calculation accuracy and clear visualisation. The results were analysed by comparing variants under different types of stress. This comparative-analytical approach allowed the identification of characteristic changes in parameters depending on the type of impact, as well as assessment of the recovery potential of typical chernozems.

To standardise the conditions for measuring electrical conductivity, total mineralisation, soil solution salinity and the content of water-soluble calcium, sodium and potassium cations, a method was used to prepare a water-soil paste in a 1:1 ratio. Soil samples were pre-dried to an air-dry state at room temperature and ground in a mortar to a homogeneous powdery state. From each prepared sample, a 10 g sample of air-dry soil was taken and placed in a chemically inert polypropylene container. Distilled water was pre-checked for electrical conductivity and salt content. In the absence of impurities, 10 ml of water was added to the soil sample, after which the mixture was intensively stirred for two minutes with a glass rod to ensure uniform moistening and activation of ion exchange (saturation). The prepared paste was kept for 24 hours in closed containers at a temperature of 20-22°C. After aging, direct measurement of the electrophysical parameters in the paste was carried out without additional filtration. Electrophysical indicators (electrical conductivity, total mineralization, salinity) were determined using the EZODO-8200 M conductometer-salinity meter (EZODO Instruments, Taiwan). The content of water-soluble calcium, sodium and potassium salts was determined using portable ion meters HORIBA LAQUAtwin (HORIBA Ltd., Japan): Na-11 (Na^+); K-11 (K^+); Ca-11 (Ca^{2+}). This approach made it possible to level out the variability of natural soil moisture, ensure the comparability of results between variants, and obtain representative data on the ionic composition of the soil solution. Soil sampling and analysis were carried out in accordance with local environmental standards and without disturbing the ecological balance, in particular in accordance with the Law of Ukraine No. 1264-XII (2025).

RESULTS

Changes in electrophysical indicators under the influence of combat operations

The results obtained allowed to assess the level of soil electrical conductivity based on the content of water-soluble salts in the soil solution, the degree of salinisation due to changes in the water regime and biological activity. In the fallow variant after thermal exposure, the electrical conductivity in the upper layer of 0-10 cm was 258 μS/cm, and the values of total mineralisation and salinity were 170 and 129 ppm, respectively. With depth, the indicators gradually decreased and in the 30-40 cm layer had values of 185 μS/cm for electrical conductivity, 122 ppm for total mineralisation and 93 ppm for salinity. This distribution indicated a decrease in the content of easily soluble salts with depth. The electrical conductivity of the typical chernozem fallow variant was 226 μS/cm in the 0-10 cm layer, total mineralisation was 149, and salinity was 113 ppm. With depth, there was an increase in the electrical conductivity of soil-water suspensions, which was 376 μS/cm, as well as mineralisation to 248 ppm and salinity to 188 ppm. Thus, the distribution of salts indicated a natural accumulation of easily soluble salts in the lower layers studied, which could be the result of biological processes, capillary moisture rise, and the absence of mechanical impact on the soil (Fig. 1).

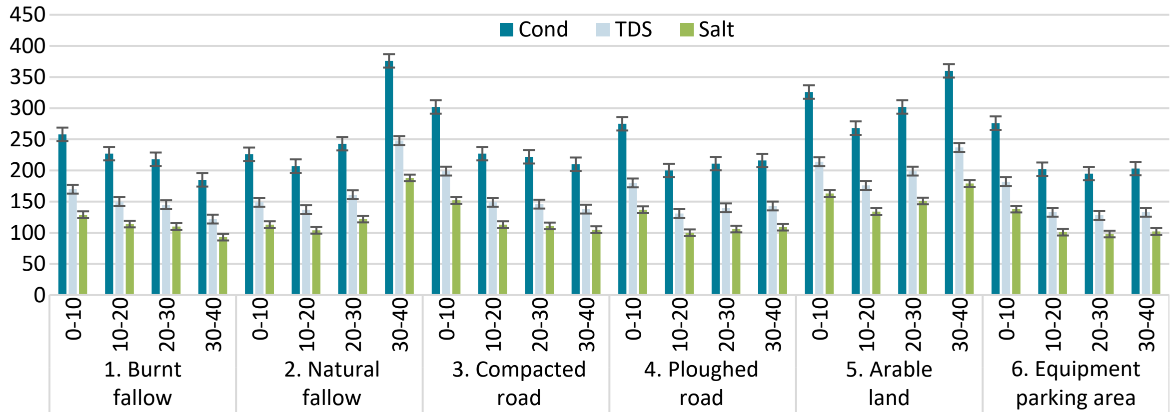

***Figure 1.** Vertical distribution of electrical conductivity, total mineralisation and salinity of typical chernozems under different types of agrogenic, technogenic and combat loads*

***Notes:** electrical conductivity (Cond), μS/cm; total dissolved solids (TDS), ppm; salinity (Salt), ppm (LSD05 Cond – 30, Salt – 25, TDS – 20)*

***Source:** created by the authors*

The surface layer of 0-10 cm on the road variant had a slightly increased level of electrical conductivity up to 302 μS/cm, as well as total mineralisation – 199 ppm and salinity – 152 ppm. However, in other studied layers from 10 to 40 cm, electrical conductivity decreased to 210-227 μS/cm, indicating an uneven distribution of easily soluble salts at different depths. The absence of a clear and gradual change in electrophysical indicators could have been caused by technogenic soil compaction, which disrupts the natural differentiation of the soil. In the ploughed road variant, the electrical conductivity in the 0-10 cm layer was 275 μS/cm, mineralisation was 180 ppm, and salinity was 137 ppm. At other studied depths from 10 to 40 cm, the electrical conductivity decreased to 200-216 μS/cm, which indicates a partial accumulation of easily soluble salts in the lower studied layers of typical chernozem.

The highest electrical conductivity values among the other studied variants were characteristic of the arable land variant and reached 326 μS/cm. The values of total mineralisation and salinity were also elevated – 214 μS/cm and 163 ppm. With depth, the electrophysical indicators decreased slightly but remained at a high level. Thus, at a depth of 30-40 cm, the electrical conductivity was 360 μS/cm. This distribution indicates the accumulation of easily soluble salts in the arable layer, which could be the result of agricultural use, fertiliser application, or insufficient drainage due to compaction of the lower soil layers and the formation of a plough pan. In the case of temporary military equipment storage, the electrical conductivity in the upper layer studied was 276 μS/cm, and the total mineralisation and salinity values were 182 and 138 ppm. At a depth of 10 to 40 cm, the electrical conductivity decreased to 195-203 μS/cm, indicating local accumulation of easily soluble salts in the surface layer of typical chernozem. This could be the result of both contamination with lubricants and disruption of the soil water regime due to its compaction.

Changes in the content of water-soluble calcium, sodium and potassium cation salts under the influence of combat operations

An analysis was conducted of the content of water-soluble calcium, potassium and sodium cation salts in typical chernozems at depths of 0 to 40 cm. The results obtained made it possible to identify the nature of the distribution of water-soluble salts depending on the type of land use, the existing anthropogenic impact, or the natural state of the study site. In the case of burnt fallow land, the content of water-soluble calcium salts was stable at all depths studied and was at the level of 93 ppm. The sodium content was quite insignificant, with a maximum value of 4 ppm in the lower soil layers. The potassium content showed a clear downward trend from 55 ppm in the surface layer of 0-10 cm to 7 ppm at depths of 20 to 40 cm, indicating its active accumulation in the surface layers of typical chernozem after a fire (Table 1).

***Table 1.** Content of water-soluble salts of calcium, sodium and potassium cations in typical chernozems affected by military operations, ppm*

Variant	Depth, cm	Content of water-soluble cation salts, ppm		
		Ca	Na	K
1. Burnt fallow	0-10	93	0	55
	10-20	93	2	20
	20-30	93	4	7
	30-40	93	4	7
2. Natural fallow	0-10	98	0	18
	10-20	110	2	6
	20-30	150	2	4
	30-40	150	2	0
3. Compacted road	0-10	130	2	25
	10-20	100	4	0
	20-30	100	5	0
	30-40	110	5	5
4. Ploughed road	0-10	130	4	11
	10-20	110	4	4
	20-30	100	4	0
	30-40	100	5	0
5. Arable land	0-10	130	2	14
	10-20	120	2	6
	20-30	140	3	0
	30-40	140	3	0
6. Equipment parking area	0-10	150	2	24
	10-20	120	2	11
	20-30	120	2	5
	30-40	110	3	0
LSD_{05}		15	2	8

***Source:** compiled by the authors*

Under the influence of natural fallow use, the calcium salt content increased from 98 ppm in the surface layer of typical chernozem to a maximum of 150 ppm at depths of 20 to 40 cm, indicating its accumulation in the lower layers. Water-soluble sodium salts were almost absent in the profile, amounting to only 0-2 ppm. The content of water-soluble potassium salts decreased from 18 ppm in the upper layer to complete absence at a depth of 30-40 cm, which could be more typical for soils in the recovery phase with increased biological activity. On the road variant, the content of water-soluble calcium salts ranged from 100 to 130 ppm without a clear distribution and decrease in content with depth. Water-soluble sodium salts increased slightly in content with depth from 2 to 5 ppm at a depth of 10-30 cm, while potassium salts had an unclear distribution pattern with a higher content in the 0-10 cm layer up to 25 ppm, a complete absence at depths of 10 to 30 cm, and a slight content at a depth of 30-40 cm – 5 ppm. The uneven distribution of water-soluble salts could have been caused by physical disturbance of the profile as a result of soil compaction by repeated passage of military equipment.

The reduction in the content of water-soluble calcium salts occurred after ploughing the road from 130 ppm to 100 ppm at depths of 20 to 40 cm. Sodium salts were consistently present throughout the entire depth studied in an amount of about 4-5 ppm. The amount of water-soluble potassium salts in the surface layers was 11 ppm, and below that, they were not detected at all. The arable land variant was characterised by an increase in the content of water-soluble calcium salts in the surface layer 0-10 cm from 130 ppm to 140 ppm at a depth of 20-40 cm, which could have been the result of mixing the upper part of the soil as a result of cultivation. Sodium salts were present in very small amounts, namely 2-3 ppm. Water-soluble potassium salts decreased from 14 ppm in the surface layer to practically no presence at depths of more than 20 cm. The highest values of water-soluble calcium salts were recorded in the variant of temporary military equipment storage, where the content was 150 ppm in the upper layer of 0-10 cm, which could be the result of local accumulation or contamination of the soil surface. With depth, the amount of calcium decreased to 110 ppm. The amount of sodium was low, at around 2-3 ppm, and water-soluble potassium salts showed a decrease from 24 ppm in the 0-10 cm layer to complete absence at a depth of 30-40 cm.

Correlation between soil electrophysical parameters

The correlation analysis of electrophysical indicators was based on averaged data within the depth range of 0-40 cm, which allowed assessing the nature of the relationships between electrical conductivity, total mineralisation, salinity, and the content of water-soluble calcium, potassium, and sodium salts in the studied variants. In general, the correlation indicated a strong positive relationship between electrical conductivity, total mineralisation and salinity, which is to be expected, since these indicators were interrelated and reflected the overall level of easily soluble salts in the soil (Table 2).

Table 2. *Correlation matrix of the dependence of electrophysical indicators of typical chernozems under the influence of combat operations*

Indicator	Cond	TDS	Salt	Ca^{2+}	Na^{+}	K^{+}
Cond	1.00	+0.98	+0.96	+0.72	+0.89	–0.35
TDS	+0.98	1.00	+0.97	+0.70	+0.87	–0.38
Salt	+0.96	+0.97	1.00	+0.68	+0.91	–0.42
Ca^{2+}	+0.72	+0.70	+0.68	1.00	+0.55	–0.48
Na^{+}	+0.89	+0.87	+0.91	+0.55	1.00	–0.36
K^{+}	–0.35	–0.38	–0.42	–0.48	–0.36	1.00

Note: *electrical conductivity (Cond); total dissolved solids (TDS); salinity (Salt); content of water-soluble salts of calcium (Ca^{2+}), sodium (Na^{+}), and potassium (K^{+})*
Source: *created by the authors*

The content of water-soluble calcium salts had a moderate positive correlation with electrical conductivity, indicating the contribution of these salts to the overall mineralisation of the soil, especially in the upper layers with a high calcium salt content. Sodium, despite its insignificant content, also had a positive correlation with electrical conductivity. In addition, on the road and ploughed road variants, a slightly higher sodium salt content correlated with increased electrical conductivity. The content of water-soluble potassium salts had a weak or even negative correlation with electrophysical indicators. In the fallow and arable land variants, a decrease in potassium salt content with depth was observed, which was not accompanied by a decrease in soil electrical conductivity. The fallow land variant showed the highest electrical conductivity, which was confirmed by the accumulation of calcium, but at the same time, sodium salts were at a low level, and potassium was not detected at all. Thus, low-mobility water-soluble salts prevailed in the profile. The arable land variant was characterised by consistently high electrical conductivity values throughout the entire soil thickness studied, which directly correlated with a high level of accumulation of easily soluble calcium salts. On the road and ploughed road variants, the electrophysical indicators had average values, but sodium accumulated the most. Electrical conductivity gradually decreased on the burnt fallow variant, which correlated with a decrease in the content of water-soluble potassium salts, but stable values of calcium salts. A correlation between the electrophysical indicators and the content of water-soluble calcium salts was found on the variant of the military equipment parking area in the surface layer of 0-10 cm.

A summary of the research results indicates a clear differentiation in the electrophysical indicators of typical chernozems depending on the nature of natural, agrogenic, technogenic and military influences. It was established that military impact caused a decrease in electrical conductivity at the studied depth (0-40 cm), uneven distribution of water-soluble salts and local accumulation of calcium and potassium in the surface layers. Variants with compaction and contamination were characterised by an increase in electrical conductivity and total mineralisation, which indicated a disturbance in the salt composition. Agrogenic use led to an increase in electrical conductivity and the amount of water-soluble salts. In the fallow use variant, natural vertical differentiation of salts was observed. The established correlations between electrical conductivity and water-soluble salt content allowed to consider electrophysical indicators as indicators of the degree of soil environment disturbance and its restoration potential.

DISCUSSION

The established patterns of profile distribution of electrical conductivity, total mineralisation and salinity, as well as their correlation with the content of water-soluble salts, are consistent with a number of recent international studies, confirming the relevance of the chosen topic. In the work of G. Kargas *et al.* (2020), a comparison was made between methods for determining soil electrical conductivity based on a soil-to-water ratio of 1:1, 1:5, and the use of a saturated paste-like extract. The researchers' goal was to evaluate the accuracy and practicality of the methods presented. The authors found that the method of determining electrical conductivity using a soil-to-water ratio of 1:1 provides stable results for field conditions, although the values may be lower than when using a saturated paste-like extract. In the studies conducted, the 1:1 water-soil paste method also demonstrated high reproducibility and allowed for standardisation of measurements between variants. This, in turn, confirmed the feasibility of choosing the method for assessing water-soluble salts in the presented research variants. It should also be noted that a 1:5 ratio was used in the previous stages of the studies, but the transition to a 1:1 ratio was due to the need to increase sensitivity to changes in the salt composition in the analysed soil samples. This approach was consistent with the conclusions of G. Kargas *et al.* who emphasised the practicality of using this ratio, particularly in conditions of limited access to laboratory equipment for preparing saturated paste.

In the publication by M. Sahana *et al.* (2020), satellite indices were used to assess soil salinity in the Sundarban region (India). The authors found that electrical conductivity was a reliable indicator for identifying areas with increased salt load, especially under conditions of anthropogenic impact. Eight salinity indices obtained from satellite images were statistically correlated with measured electrical conductivity values using Pearson's correlation coefficient, confirming its diagnostic value. A similar relationship was established in this study, where the correlation coefficients between electrical conductivity and salt content ranged from +0.68 to +0.91, indicating a strong direct relationship. Researchers I. Stavi *et al.* (2021) examined the mechanisms of soil degradation in arid regions, particularly under the influence of sodium. The authors emphasised that excess sodium in the soil solution caused the dispersion of clay particles, deterioration of structure and reduced aeration, which decreased biological activity and plant productivity. It was also noted that sodium competed with other cations (especially potassium and ammonium) for absorption. Within the scope of the studies, despite the low values of sodium salts, a strong positive correlation was found between electrical conductivity and its concentration (+0.89). At the same time, the negative correlation with potassium (-0.35) was consistent with the mechanism of ion competition and potential salt leaching.

In the article by I.W. Primadipta *et al.* (2025), Landsat 8 data was used to monitor soil salinisation dynamics. It was found that soil electrical conductivity varied depending on the type of land use and the presence of anthropogenic load, particularly in areas of intensive construction and transport infrastructure. These results were comparable for road sections and equipment parking areas, where uneven distribution of salts with depth was recorded. Studies conducted by D. Ma *et al.* (2023) established the spatial and temporal dynamics of land use changes in the chernozem region of China. It was found that intensive land use over the past decades has been accompanied by land degradation, in particular a deterioration in physical and chemical properties and a loss of ecological functions. As a result of the research conducted under conditions of disturbed water regime, uneven distribution of salts and reduced electrical conductivity were recorded, indicating degradation processes associated with land use characteristics. X. Wan *et al*. (2025) found that soil electrical conductivity had a strong positive correlation with the concentration of ions, in particular sodium, as well as chlorides and sulphates, which allowed the indicator to be used as a salinity indicator. The studies also obtained electrical conductivity values accompanied by an uneven distribution of water-soluble salts, especially in the upper layer.

M.C. Paz *et al*. (2020) used electromagnetic tomography to monitor salinisation dynamics, showing that electrical conductivity varied in time and space depending on hydrological conditions, including drainage, evaporation and salt depth. The patterns identified confirmed the spatial heterogeneity of water-soluble salt content observed in the upper layers of the studied areas with disturbed water balance. M.A. Elshewy *et al*. (2024) developed a model for assessing soil salinity based on satellite data. The authors established a significant correlation between spectral indices and laboratory-measured electrical conductivity, which allowed for rapid assessment of the salt regime over large areas without the need for mass field sampling of soil. This approach was particularly relevant for regions with high spatial variation in salinity. Y. Zhang *et al*. (2025) formulated the statement that poor water infiltration can lead to poor drainage, waterlogging and increased electrical conductivity. For example, on a section of road where the soil had been compacted by repeated movement of military equipment, the electrical conductivity in the upper 10 cm layer was 302 μS/cm, the total mineralisation was 199 ppm, and the salinity was 152 ppm. This indicated a disturbance in the water regime, which caused local accumulation of salts.

I.V. Chushkina *et al*. (2021) noted that soil electrical conductivity is an integral indicator that reflects a combination of physicochemical properties, such as moisture, soil solution mineralisation, cation solution capacity, granulometric composition, and organic matter. A change in any of these parameters in space or time is accompanied by variability in soil electrical conductivity, which allows it to be used as an indicator of the stability or dynamics of the soil environment. The results of the studies confirmed the sensitivity of electrophysical indicators to changes in the composition of the soil solution and showed a strong positive correlation of electrical conductivity, for example, with total mineralisation (+0.98), salinity (+0.96), and the content of water-soluble calcium (+0.72) and sodium (+0.89) salts. To ensure the comparability of soil electrical conductivity results in field conditions, two approaches are used: measurement in soil with field moisture and under conditions of artificial moistening to full moisture capacity. As noted in the studies by M.M. Omar *et al*. (2024), methods with a fixed soil: water ratio allowed to level out the variability of moisture as one of the most influential factors on electrical conductivity. Thus, a similar approach was used in the studies, where the soil paste was prepared by mixing 10 g of air-dry soil with 10 ml of distilled water, kept for 24 hours, and then measured. This allowed to standardise the conditions for determining electrical conductivity, total mineralisation, salinity, and the content of water-soluble calcium, sodium, and potassium cations.

The application of mineral fertilisers increases soil electrical conductivity due to the influx of cations (Ca^{2+}, K^+, Mg^{2+}, NH_4^+) and anions (NO_3^-, SO_4^{2-}, Cl^-) into the soil solution. As shown in a study by M.S. Kaufmann *et al*. (2025), electromagnetic induction allows for spatial tracking of fertilisation effects, in particular the accumulation of nitrates and macronutrients, which directly correlates with an increase in electrical conductivity. Thus, on arable land, electrical conductivity exceeded 300 μS/cm, accompanied by a high content of water-soluble calcium salts up to 150 ppm and potassium up to 24 ppm. This indicated the accumulation of nutrients and their contribution to soil electrical conductivity. Within the studied areas of typical chernozems, it was found that electrical conductivity, total mineralisation and salinity decreased with depth. The highest values were observed in the upper studied layers, which is associated with the accumulation of salts. Similar vertical differentiation is confirmed by Yu. Shaforost *et al*. (2024), who pointed to an increase in electrical conductivity in the upper layers due to a higher concentration of ions. Also, in the fallow variant after burning, electrical conductivity decreased from 258 μS/cm to 185 μS/cm, and calcium content decreased from 55 to 7 ppm. A similar trend was observed in the road and equipment parking variants, indicating surface enrichment with salts. This was consistent with the data of Q. Baloch *et al*. (2025), who recorded similar patterns in semi-arid conditions. Soil electrical conductivity may be one of the key parameters characterising its quality, health and productivity. As noted by L. Gong (2022), it is electrical conductivity that affects yield, nutrient availability and microbiological activity, and Atlas Scientific (2023) emphasised its role in the transport of ions in soil solution. Thus, studies of electrical conductivity proved to be a sensitive indicator of soil condition, which was related to the content of water-soluble calcium, sodium, and potassium salts, confirming its diagnostic value for assessing the salt regime and land use efficiency. The results of the study of the electrophysical indicators of typical chernozems, which were in natural cover conditions and were also subjected to agrogenic, technogenic and combat influences, confirmed the high sensitivity of electrical conductivity to changes in the ionic composition and salt content in the soil solution.

CONCLUSIONS

Based on a comprehensive analysis of electrophysical indicators and the content of water-soluble cation salts in typical chernozems that have been subjected to various types of impact, including natural, agrogenic, technogenic, and combat, it was established that the distribution of water-soluble salts and the electrical conductivity of the soil solution varied significantly depending on the type of load. Natural variants had a clearly expressed vertical differentiation of easily soluble salts, with a gradual decrease in electrical conductivity at the studied depths. The lowest values of up to 185 μS/cm were recorded in the lower horizons of typical fallow chernozem. In contrast, areas that had been subjected to military impact (compaction, burning, contamination) were characterised by uneven distribution of salts with depth and their local accumulation in the upper layers. The highest electrical conductivity values of up to 360 μS/cm were observed on arable land, which could be the result of anthropogenic impact (fertiliser application) and the parking of machinery – up to 302 μS/cm, which also indicated technogenic enrichment of the soil solution. According to the results of the analysis of the content of water-soluble cation salts, it was established that the amount of calcium was the highest in the studied variants, where its content reached 150 ppm, sodium was the lowest, and the amount of potassium depended on the nature of the impact and use of typical chernozems. In natural variants, a gradual accumulation of calcium and a decrease in potassium to 7 ppm was observed, while technologically disturbed variants as a result of hostilities had a disturbed profile and a differentiated distribution of salts at the studied depths.

A stable positive correlation was established between electrical conductivity and the content of calcium (+0.72) and sodium (+0.98) salts, which confirmed the diagnostic informativeness of electrophysical indicators for assessing the degree of soil environment disturbance. A negative correlation with potassium (-0.35) could indicate its loss or accumulation under certain types of impact in the surface layers studied, in particular burning (thermal degradation). The method of preparing a water-soil paste in a 1:1 ratio with an exposure time of 24 hours ensured the stability of the measurement conditions, levelled out the influence of humidity and allowed for comparable results between the variants. This confirmed the feasibility of using standardised approaches to assess the salt regime in degraded chernozem soils. It was found that electrical conductivity can be used not only as an indicator of salinisation, but also as an operational indicator of the degree of anthropogenic disturbance, in particular in cases of local pollution, compaction and thermal damage. The results obtained are part of a broader study of the physical properties of soils disturbed by military operations. In further stages, it is planned to supplement the study with the determination of density, porosity, dispersibility, hardness, moisture capacity, etc., and to establish their connection with microbiological characteristics, which will allow the formation of a comprehensive model of agrophysical degradation of militarily damaged chernozems.

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Електрофізичні показники чорноземів типових під впливом бойових дій та техногенного навантаження

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Анотація. У статті представлено результати дослідження електрофізичних показників типових чорноземів, що зазнали впливу бойових дій та техногенного навантаження, а також агрогенного використання. Метою роботи було виявлення змін електропровідності, загальної мінералізації, солоності та вмісту водорозчинних солей катіонів кальцію натрію і калію шляхом порівняння ділянок із різним типом техногенного, агрогенного та постагрогенного навантаження. Згідно із методологією відбір зразків було проведено від 0 до 40 см через кожні 10 см. Вимірювання електрофізичних параметрів проводилося у водно-ґрунтово пасті (1:1) за допомогою кондуктометра EZODO-8200 M та іономірів HORIBA LAQUAtwin. Додатково було встановлено кореляційні зв'язки між електропровідністю, загальною мінералізацією, солоністю та вмістом водорозчинних солей. Бойовий вплив спричиняв зниження електропровідності з глибиною, нерівномірний розподіл та накопичення солей натрію та калію у верхніх шарах. На випаленому перелозі електропровідність знижувалась із 258 до 185 мкСм/см а вміст солей калію від 55 до 7 мг/л. У варіантах дороги та стояння техніки спостерігалося підвищення електропровідності (до 302 мкСм/см) та накопичення солей кальцію до 150 мг/л і калію – до 24 мг/л. У варіанті ріллі електропровідність залишалася стабільно високою (до 360 мкСм/см), що викликано агрогенним накопиченням солей. На розораній ділянці дороги показники були помірними, що свідчило про часткове відновлення. Встановлено сильну кореляцію електропровідності з кальцієм (+0,72) та натрієм (+0,89), а також негативну з калієм (-0,35). Практичне значення отриманих результатів дослідження полягає в можливості використання електропровідності та вмісту водорозчинних солей як індикатора ступеня порушення ґрунтового середовища, що дозволило оперативно оцінювати деградацію агрогенних та техногенно порушених ділянок чорноземів унаслідок бойових дій, а також можливості формування рекомендацій щодо відновлення ґрунтового покриву в умовах постконфліктного землекористування

Ключові слова: мілітарна деградація; електропровідність; водорозчинні солі; постконфліктне землекористування; агрогенне використання; перелогове використання