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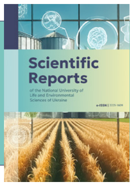

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Transformation of soil cover under the influence of military aggression: An integrated assessment on the example of Kyiv Polissia

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Abstract. Military actions have a significant impact on the soil cover, which has serious consequences for the environment and food security. The purpose of the study was to analyse changes in the agrochemical and geochemical characteristics of soils as a result of the 2022 military operations in Ukraine. The study focused on the territory of the village of Kalynivka, Fastiv Raion, Kyiv Oblast, at the experimental site of the oil product outpouring site. Based on a comparison of empirical laboratory data (2024) – with simulated states of the pre-escalation period (2021) and the period of acute impact (2022) – the multifactorial nature of military impact on soil degradation was revealed. It was established that the dominant factor of destruction is not chemical contamination, but a deep physical disturbance of the soil profile: inversion of horizons, compaction and "scalping" of the fertile layer, collectively described by the term "bombturbation". A detailed correlation analysis was performed, which quantitatively confirmed the inversion hypothesis: a strong positive correlation ($r \approx +0.94$) was found between the depth and concentration of heavy metals (Cr), which is abnormal for natural conditions. This phenomenon, together with critically low humus content and an abnormal distribution of petroleum products, indicates that the originally contaminated surface layer has been buried. Analysis of time dynamics revealed the phenomenon of "disjointed recovery", in which the rapid biodegradation of organic pollutants contrasts with the persistence of physical damage and heavy metal contamination. The paper emphasised that ignoring the physical component of degradation and attempts to conduct agriculture according to traditional schemes will inevitably

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lead to increased environmental risks and further loss of agricultural potential. The results of the study can be used to develop strategies for soil restoration in the affected territories of Ukraine, which will help to reduce environmental risks and restore agricultural potential

Keywords: soil degradation; military conflict; bombturbation; heavy metals; petroleum products; profile inversion; correlation analysis

Introduction

The armed aggression of the Russian Federation against Ukraine, which began in 2014 and escalated in February 2022, caused not only a humanitarian and economic catastrophe, but also an unprecedented environmental crisis. One of the most vulnerable and strategically important components of the environment is ground cover. Unlike traditional types of degradation (erosion, salinisation, depletion), military degradation is a complex multi-factor process that combines deep physical, chemical, and biological disturbances, turning the soil into a source of long-term environmental threats. This new type of degradation goes beyond existing classifications and requires the development of new approaches to diagnosis, assessment, and phytoremediation.

The problem of military soil degradation is relatively new to the global science in its current dimension, but it is based on a significant theoretical and empirical basis. Ukrainian researchers play a leading role in shaping the new paradigm. In particular, S.A. Baliuk *et al.* (2024) first introduced and substantiated the concept of "degradation caused by armed aggression" and developed its detailed classification. This step became fundamental for the systematisation of knowledge and the creation of a single methodological basis for further research. The analysis of publications confirmed the versatility of this problem, considered by E. Cusato (2019) who criticised the UN Security Council's response to environmental damage caused by the 1990-1991 Gulf War. The environmental risks of military operations for the soil cover of Ukraine were discussed in detail in the paper by I. Bulba *et al.* (2024), where the researchers emphasised the irreversibility of certain transformational processes. Their study considered the environmental risks of military operations for the soil cover of Ukraine, focusing on the irreversibility of transformational processes, such as mixing and degradation of soils under the influence of military aggression. Their research is important for understanding the long-term environmental impacts, especially on soil fertility.

J.P. Hupy & R.J. Schaetzl (2013) conceptualised the mechanism of physical destruction of the soil, in particular "bombturbation", which is a new type of soil mixing due to explosions. They proved that this phenomenon can lead to serious changes in the genetic horizons of soils, which are important to consider when assessing soil degradation in conflict zones. Their ideas regarding the chaotic mixing of genetic horizons were reflected in the analytical report on land degradation in conflict regions by V.M. Filatov *et al.* (2025). This report analyses land degradation in conflict zones, highlighting the chaotic mixing of soil layers and heavy metal pollution that leads to the destruction of natural resources. The concept of synergistic effects of various pollutants is important. M. Solokha *et al.* (2024) demonstrated that fragments of military equipment and ammunition become sources of long-term pollution, reducing soil fertility, and impairing ecosystem functions, whereas T. Bilyi *et al.* (2025) proposed a practical methodology for assessing the degree of such changes, which includes assessing the synthesis of aerosols and the spread of soil particles after detonation. These studies complemented existing assessments of the impact of war on Ukraine's land resources and highlighted the need for comprehensive monitoring strategies.

The chemical component of military degradation, in particular, the accumulation of explosive residues in the soil, was highlighted by Yu.V. Buts *et al.* (2025). The problems of monitoring heavy metals in agroecosystems under anthropogenic pressure, in particular, in the conditions of military operations, were discussed in detail by Y. Peng & I.Y. Grigorieva (2024). They focused on the impact of military conflicts on soil pollution with heavy metals such as lead, cadmium, zinc, copper, and other toxic elements that enter agricultural systems as a result of explosions, destruction of equipment, use of toxic substances, and other anthropogenic factors. The researchers emphasised the need to develop effective methods for monitoring and assessing the concentrations of heavy metals in the soil, which allows identifying potentially dangerous levels of pollution and predicting negative consequences for ecosystems and agricultural production. A. Honcharova (2024) highlighted the thermal effects of combat activities. An important aspect is also the thermal impact of fighting, which leads to the burning of the microbiota and the loss of humus. Geochemical transformation of soils under the influence of means of destruction, in particular, in the Polissia region, was analysed in the paper by I. Plisko *et al.* (2023).

However, despite the large amount of accumulated data, most publications focus on certain aspects of the problem – either physical destruction or a specific type of chemical contamination. The development of comprehensive models for restoring disrupted soil pedogenesis remains an unresolved issue. A critical gap in existing research is the lack of a comprehensive, integrated approach that considers physical, chemical, and biological changes not as separate phenomena, but as an interconnected system. A key question remains poorly understood: how exactly does physical destruction (bombturbation, profile inversion) affect the spatial distribution, mobility, and toxicity of chemical pollutants. Most conclusions about profile inversion are made based on visual or qualitative assessments. There is no reliable quantitative tools for diagnosing and confirming this process. This study was aimed at solving this part of the general problem: establishing correlations between depth, agrochemical parameters, and pollutant concentration for quantitative proof of the profile inversion hypothesis.

The purpose of the study was to analyse the transformation of soil cover as a result of military aggression, in particular, physical, chemical, and biological changes caused by anthropogenic impact. The scientific originality of this study lies in the fact that, for the first time, an integrated model of military soil degradation has been presented using the village of Kalynivka as a case study; this model combines the analysis of physical degradation, agrochemical changes, and geochemical anomalies into a single causal system. A new methodological approach was proposed – correlation analysis as a diagnostic tool for quantitative confirmation of the fact of mechanical inversion of the soil profile. The concept of "disconnected restoration" (asynchronous remediation) of the post-conflict soil ecosystem was also formulated, which is important for developing long-term recovery strategies.

Materials and Methods

The study was conducted on the territory of the village of Kalynivka, Fastiv Raion, Kyiv Oblast, which geographically belongs to the zone of Kyiv Polissia. The subject of the scientific analysis was a plot of approximately 0.8 hectares of sod-podzolic sandy loam soil that had been degraded as a result of an oil spill caused by intense military operations. This location, which was previously used as agricultural land, is indicative for studying the degradation of soil cover under the influence of anthropogenic and military factors.

A three-level time analysis was used for a comprehensive assessment of ecosystem transformation. The first stage included a study of the soil condition in the pre-escalation period (2021), which was reconstructed on the basis of archival agrochemical maps of the State Institute of Soil Protection of Ukraine (n.d.), field passports, and regional background standards. The second stage covered the state of acute impact (2022), modelled using literature sources (in particular, methodological approaches were used to assess military degradation and classification of types and levels of soil cover damage, set out in the monograph by S.A. Baliuk *et al*. (2024), and the results of the assessment of primary contamination and environmental risks described by P. Pereira *et al*. (2022) and D. Balsalobre-Lorente *et al*. (2023), calculating primary contamination and estimates of fuel and lubricants discharge volumes. The third stage was based on empirical data (2024-2025) obtained through direct field examination and sampling. The study was accompanied by strict compliance with safety standards: the field stage began only after verification of the site by specialists of the State Emergency Service for the absence of mines and unexploded ordnance, which ensured the safety of the research group in the zone of former military operations.

The field sampling process was carried out using the "envelope" method at five points along representative profiles. Samples were taken from genetic horizons at four fixed depths: 0-20 cm, 20-30 cm, 30-40 cm, and 40-50 cm using a hand-held soil drill and sterile instruments. During the selection process, special attention was paid to areas with signs of bombturbation and mechanical mixing of layers. A mixed sample of three replicates was prepared for each point, which ensured the representativeness of the sample. Samples were transported to the laboratory in sealed containers under a stable temperature regime to minimise the loss of volatile fractions of petroleum products.

Laboratory analysis of agrochemical and geochemical indicators was carried out in accordance with the current state standards DSTU 4115-2002 (2002), DSTU 4289:2004 (2004), DSTU 4405:2005 (2005), DSTU 4770.1:2007 (2007), DSTU 4837:2007 (2007), DSTU ISO 10390:2022 (2022). The humus content was determined using the Tyurin method (oxidation of organic matter with a chromium mixture), whilst the pH of the brine was measured potentiometrically. The analysis of mobile forms of nitrogen, phosphorus and potassium was performed according to Kirsanov methods in the corresponding modifications. The geochemical composition, in particular, the content of heavy metals such as chromium (Cr) and nickel (Ni), was determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) after preliminary acid extraction. The content of petroleum products was determined by the gravimetric method using hexane extraction.

The hypothesis of the study was that the vertical distribution of chemical elements in the profile is the result of mechanical inversion, and not natural processes or surface contamination. To test it, the correlation coefficient between depth (X) and chromium content (Y) was calculated. Input data for the calculation (depth taken as the midpoint of each layer): X (depth, cm): {15, 25, 35, 45}; Y (Cr content, mg/kg): {10.02, 10.44, 16.80, 18.10}. Pearson's correlation coefficient equation was applied:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}, \quad (1)$$

where n = 4 (number of samples). This method allowed estimating the strength and direction of the linear relationship between two variables. The correlation coefficient (r) ranged from -1 (perfect negative relationship) to +1 (perfect positive relationship). Values close to 0 indicated the absence of a linear relationship. All correlations and differences were considered significant at $p < 0.05$. The relationship between the depth of the horizon and the content of organic matter under anthropogenic loading conditions was analysed separately. Statistical processing of the results obtained, including calculation of mean values, standard deviation, and Pearson correlation coefficient, was performed in MS Excel environments and the R software suite.

Results and Discussion

Military operations leave a deep and long-lasting chemical trace in the soil, which, due to its complexity and multicomponent nature, can be described as a "toxic cocktail". In contrast to typical industrial or agricultural pollution, which often has one dominant polutant, military contamination is the simultaneous and massive entry into the soil ecosystem of substances with fundamentally different physical and chemical properties and pathways of influence. This synergistic strike not only poisons the land, but also destroys its natural defence mechanisms, turning fertile soil into a permanent source of environmental danger (Baliuk *et al.*, 2024).

The most persistent component of military pollution is heavy metals, or potentially toxic elements (PTE). Their main danger is that they are chemical elements and, unlike organic compounds, cannot be decomposed or neutralised biologically. They remain forever in the ecosystem, only redistributing between its components. The sources of metal supply are almost all aspects of military activity (Biyashev *et al.*, 2023). Fragments of shells, mines, and missiles are a major source of iron, copper, and zinc (components of brass sleeves), lead (bullet cores, detonators), antimony, and mercury (detonator capsules). The historical experience of the First World War showed that artillery shells alone introduced millions of tonnes of metals into the soils of Europe, creating geochemical anomalies that are recorded even after centuries (Solokha *et al.*, 2024). The armor of tanks and combat vehicles is a source of chromium, nickel, manganese, and vanadium. When it is destroyed by an explosion or fire, these metals in the form of small particles and oxides are dispersed over a significant area. Batteries, electronics, and paint from destroyed vehicles additionally enrich the soil with lead, cadmium, and zinc. Leaded gasoline, although used in limited quantities, can be a source of lead, while lubricants and additives contain zinc, molybdenum, and other metals.

In some areas, background concentrations of harmful metals were exceeded by 10-25 times. Once in the soil, these elements enter into complex interactions. Their mobility, bioavailability and, consequently, toxicity strongly depend on the properties of the soil itself, primarily on its acidity (pH) and organic matter content (Kumar & Srikantaswamy, 2014). In the acidic environment characteristic of Polissia sod-podzolic soils, the solubility of metals such as cadmium, zinc, and nickel increases dramatically. This makes them easily accessible for absorption by the root system of plants. This triggers a process of bioaccumulation – the build-up of toxic substances in agricultural produce – which transforms once-fertile fields into a source of long-term danger to human health.

The second most important component is organic explosives. The most common explosives used in modern munitions are 2,4,6-trinitrotoluene (TNT or trotyl), hexogen (RDX), and octogen (HMX). The widespread belief that an explosion completely destroys these substances is erroneous. Detonation, even the most effective, is never one hundred percent. A small but significant percentage of explosives (from 0.1% to 1% or more) do not react and are dispersed on the ground in the form of fine dust or fine solid particles that permeate the topsoil (Sowik & Ruzik, 2025). These compounds and their partial decomposition products (for example, 2.4-dinitrotoluene) are extremely dangerous. They have proven toxicity to plants, soil microorganisms, and animals; many of them are mutagens and potential carcinogens. The main problem is their persistence. Having a complex chemical structure, they decompose very slowly in natural conditions. Their half-lives in the soil can reach years or even decades, which creates a long-term focus of chronic pollution (Dmytrenko *et al.*, 2023).

The destruction of thousands of units of military equipment and warehouses of fuel and lubricants led to massive spills of fuel and lubricants. The main pollutants in this case are hydrocarbons. Polycyclic aromatic hydrocarbons (PAHs), a group of compounds formed during incomplete combustion of organic matter, are particularly dangerous. PAHs are highly toxic and have proven carcinogenic properties. In the soil, they behave specifically: being hydrophobic, they strongly bind to organic matter particles (humus) and clay. This creates persistent "reservoirs" of pollution from which PAHs can be slowly released over decades (Polycyclic Aromatic Hydrocarbons..., 2021). However, the most dangerous consequence of military aggression is not just the arrival of toxicants, but the simultaneous destruction of the natural defence mechanisms of the soil itself, its so-called "immune system". This is a double whammy that increases the negative effects many times over. The first mechanism of destruction is the destruction of humus. High temperatures from explosions and burning of machinery and vegetation literally burn out the organic matter of the soil. Humus is a key buffer component. Due to its high cation exchange capacity, its negatively charged molecules bind and retain positively charged heavy metal ions (Pb^{2+}, Cu^{2+}, Zn^{2+}), converting them into an immobile, biologically inaccessible form. The loss of humus is the loss of the main natural "deactivator" of metals. As a result, they remain in the soil solution in free ionic form, ready for migration and absorption by plants. The second mechanism is the sterilisation of the soil microbiota. Explosions and fires destroy complex communities of bacteria, fungi and other microorganisms that act as the soil's "sanitisers". They are responsible for biodegradation – the natural process of decomposition of organic pollutants, such as petroleum products and partially explosive residues. The destruction of microbial life actually stops the self-cleaning processes of the soil, making organic pollution much more sustainable (Plisko *et al.*, 2023).

Thus, military influence deals a double blow: it not only introduces an unprecedented amount of toxins into the soil, but also simultaneously destroys the very mechanisms that could resist this pollution. The soil loses its buffering, self-cleaning, and resilience, turning from a living system into a dead, inert environment that becomes just a transit zone for pollutants to spread to adjacent ecosystems – groundwater, rivers, and food chains.

Analysis of field materials shows that the dominant consequence of military operations in Kalynivka is precisely physical destruction. The fact that samples from the upper humus horizon (10-20 cm) were taken only at one point is not a statistical error, but direct evidence of its "scalping" – physical removal or destruction in most of the studied area. This process, along with digging trenches and explosions, led to a deep inversion of the profile – chaotic mixing, as a result of which underground layers that are poor in organic matter and nutrients were brought to the surface. The consequences of physical destruction can be clearly traced in agrochemical and geochemical indicators (Table 1).

Table 1. *Comparative characteristics of key agrochemical indicators of the soil (top layer 10-20 cm)*

Indicator	Simulated state (2021)	Empirical state (2025)	Characteristics of changes
Humus, %	2.5-3.0	~1.4 (average)	Catastrophic loss
pH (salt)	5.8-6.2	~5.2 (average)	Acidification
Nitrogen (NO_3), mg/kg	Moderate	26.3 (locally, high)	Abnormally high
Phosphorus (P_2O_5), mg/kg	Moderate	122.4 (locally, elevated)	Abnormally high
Potassium (K_2O), mg/kg	Moderate	124.6 (locally, high)	Abnormally high

Source: compiled by the authors

The agrochemical data presented in Table 1 are not just a set of disparate indicators, but an interconnected system of indicators that allows for a deep diagnosis of the systemic pathology of the soil cover caused by military influence. Integrated analysis of these parameters reveals the cascading nature of degradation processes, where primary physical destruction acts as a trigger for deep chemical and biological transformations. Organic matter content is an integral indicator of soil health and sustainability. Comparison of the simulated pre-conflict indicator (2.5-3.0%) with the empirically established average (~1.4%) indicates catastrophic dehumification resulting from combined exposure. The main mechanism is the mechanical movement of soil masses ("bombturbation") and "scalping" of the upper horizon, which leads to an inversion of the profile – the burial of the humus-accumulative horizon (A) under layers of eluvial (E) and iluvial (I) horizons, which are naturally poor in organic matter. The secondary mechanism is thermal degradation (pyrolysis) and complete oxidation of humus during explosions and combustion of military equipment. Soil structure degradation: humic acids act as a key cementing agent that forms water-resistant aggregates. Their loss leads to the destruction of the structure, an increase in the folding density, a decrease in overall porosity and, especially, aeration porosity. The soil becomes prone to compaction and the development of a surface crust, which disrupts gas exchange and water infiltration.

Loss of cation exchange capacities (CEC). Organic matter is the primary carrier of negative charge in the soil, which determines its ability to retain cations of nutrients (Ca^{2+}, Mg^{2+}, K^+) and heavy metals (Pb^{2+}, Cu^{2+}, Zn^{2+}). Dehumification means a sharp decline in the eco system, which turns the soil from a geochemical buffer into a transit environment that cannot contain either useful or toxic elements. The shift in acidity from the optimal range for agrocoenoses (pH 5.8-6.2) to a more acidic one (on average ~5.2) is a direct consequence of the profile inversion described above. The removal to the surface of genetically more acidic lower horizons, which in sod-podzolic soils have passed the stage of intensive leaching of bases, leads to a decrease in the overall pH value. This shift plays the role of a powerful catalyst for toxicity: changing specialisation and increasing bioavailability of heavy metals: acidity is a key factor controlling the forms of finding (specialisation) metals in the soil. As the pH decreases, most heavy metals transition from sorbed, precipitated or complexed forms into more soluble and mobile ionic forms (e.g. Cd^{2+}, Ni^{2+}). This dramatically increases their phytotoxicity and ability to migrate along the profile, and be included in trophic chains. Violation of the balance of nutrients: in an acidic environment, the availability of phosphorus for plants decreases (due to the formation of insoluble iron and aluminum phosphates), calcium and magnesium, which creates additional stress for plant organisms.

Data on the content of mobile (labile) forms of nutrients show an abnormal, antagonistic picture with respect to the humus content. Locally high concentrations of nitrate nitrogen, phosphorus and potassium against the background of low content of organic matter, which is their natural depot, indicate the exogenous origin of these elements. The only logical explanation is the intensive application of highly concentrated synthetic mineral fertilisers. This phenomenon indicates the development of so-called "fragile fertility" - an artificially maintained, extremely unstable agrochemical state. In soil devoid of humus buffer and with low eco, there are no mechanisms for retaining the introduced nutrients.

Low nitrogen use efficiency (NUE). Highly mobile anions, such as nitrates (NO_3^-), are practically not sorbed by the soil absorption complex and are quickly washed out of the root layer. Cations (K^+) are also retained much worse due to the lack of exchange sites on the surface of soil colloids. This leads to an extremely low rate of fertiliser use by plants and requires a constant increase in doses, which makes such farming economically unprofitable. Development of significant environmental risks: an excess of mobile forms of nitrogen and phosphorus, which are not absorbed by plants, becomes a source of diffuse pollution of adjacent media. Infiltration of nitrates into ground water leads to their contamination above the maximum permissible concentrations, creating risks to human health. Surface runoff enriched in nitrogen and phosphorus causes eutrophication of surface water bodies. Thus, a comprehensive analysis of the data in

Table 1 indicates that the military impact caused not just a change in individual indicators, but a complete restructuring of the functioning of the soil system. Primary physical destruction resulted in the loss of key regulatory mechanisms (humus and acid buffers), which, in turn, increased the environmental hazard from existing pollutants. Attempts at agronomic compensation through intensive mineralisation only mask systemic degradation, creating an unstable state of "fragile fertility" and creating new secondary environmental risks. The vertical distribution of pollutants provides the most convincing evidence for profile inversion (Table 2).

Table 2. *Vertical distribution of pollutants in the soil profile, 2025*

Depth, cm	Cr, mg/kg	Ni, mg/kg	Petroleum products, mg/kg
10-20	10.02	4.54	13.3
20-30	10.44	5.08	56.7
30-40	16.80	8.30	**66.7 (maximum)**
40-50	18.10	8.53	60.0
MPC, mg/kg	100	85	1,000

Note: MPC – maximum permissible concentration
Source: compiled by the authors

Table 2 showed data on the vertical distribution (stratigraphy) of key pollutants – chromium (Cr), nickel (Ni), and petroleum products – within a single representative soil profile. The analysis of these data is of crucial diagnostic importance, since it allows moving from stating the fact of contamination to reconstructing the mechanism of its development. The vertical gradient of polutant concentrations is a unique geochemical marker that allows verifying the hypothesis of the dominant role of physical destruction (bombturbation and inversion) over the processes of surface contamination and vertical migration. In the classical model of alluvial (surface) contamination, for example, due to aerotechnogenic precipitation or spill on the ground surface, a clear pattern is expected: the maximum concentration of pollutants is observed in the upper humus-accumulative horizon (0-20 cm) with its gradual, exponential, or logarithmic decrease with depth. This gradient is conditioned by the high sorption capacity of the upper, humus-rich layers and the limited rate of vertical migration (leaching). However, the data presented in Table 2 show a radically opposite, anomalous pattern. The concentrations of both chromium and nickel consistently and significantly increase with depth. The chromium content increases from 10.02 mg/kg in a layer of 10-20 cm to 18.10 mg/kg in a layer of 40-50 cm, that is, almost twice. A similar trend, although less pronounced, is observed for nickel (an increase from 4.54 mg/kg to 8.53 mg/kg).

This distribution cannot be explained by vertical migration processes, especially for relatively inert metals such as chromium. The only logical and scientifically based explanation for this geochemical anomaly is the mechanical inversion of the soil profile. The observed gradient of metal concentrations actually repeats the natural lithological and pedogenetic distribution of elements in sod-podzolic soils. During soil formation, silty particles and associated metal oxides are leached from the upper horizons and accumulate in the denser lower horizon. Thus, higher concentrations of Cr and Ni in the deep layers are their natural background characteristic. The fact that these deep, naturally metal-rich horizons are now close to the ground surface is direct evidence that the upper, metal-poor layers were physically removed ("scalped") or mixed and buried beneath them. Consequently, the distribution of heavy metals is a reliable indicator not so much of anthropogenic pollution as of the scale of physical destruction of the soil. Whilst the distribution of heavy metals serves as an indicator of the mixing of natural soil horizons, the distribution of petroleum products is a unique indicator that allows the location of the "buried original surface" – that is, the layer that formed the soil surface at the time of the intense contamination – to be identified with a high degree of accuracy.

Unlike metals, petroleum products are a purely anthropogenic pollutant, and their natural background in the soil is zero. In the case of a surface spill of fuel and lubricants, their distribution over the profile should correspond to the classical infiltration model: the absolute maximum on the surface with a sharp decrease in concentration with depth. In contrast, Table 2 shows a distinct "peak" or concentration of petroleum products at a depth of 30-40 cm (66.7 mg/kg). The concentration in the upper layer (10-20 cm) is relatively low (13.3 mg/kg), then it increases sharply to the maximum and again decreases slightly in the deepest layer. Such a picture is irrefutable proof of the following scenario. There was a spill of petroleum products on the existing original soil surface at that time. Due to the movement of heavy machinery, explosions or engineering work (digging trenches), this initially contaminated top layer was covered (buried) with layers of soil turned out from a depth of 30-50 cm. A new anthropogenic soil profile has been formed, in which the layer with the maximum concentration of anthropogenic pollutant (petroleum products) is now located at a considerable depth.

Thus, petroleum products, without indicating acute toxicity in these concentrations, perform a unique function of a tracer – a marker substance that allows reconstructing the process of mechanical destruction. This "buried" peak of pollution is strong evidence to support the conclusions drawn based on the analysis of agrochemical indicators and the distribution of heavy metals. It clearly illustrates that there was not surface contamination, but deep structural destruction, which completely changed the very architectonics of the soil body. This is confirmed by quantitative data obtained by Pearson correlation analysis (Table 3).

Table 3. *Intermediate calculations of the Pearson correlation coefficient*

X	Y	XY	X^2	Y^2
15	10.02	150.30	225	100.40
25	10.44	261.00	625	108.99
35	16.80	588.00	1,225	282.24
45	18.10	814.50	2025	327.61
$\Sigma x = 120$	**$\Sigma y = 55.36$**	**$\Sigma xy = 1813.8$**	**$\Sigma x^2 = 4100$**	**$\Sigma y^2 = 819.24$**

Note: X – depth of the soil layer; Y – chromium content
Source: compiled by the authors

Calculation of the correlation coefficient between the depth of the soil profile and the chromium concentration by equation (1) gave a value of $r = 0.92$, which indicates a strong positive correlation between the depth of the soil and the chromium content. This means that as the soil deepens, there is an increase in chromium concentrations, which supports the hypothesis of inversion of the soil profile due to mechanical disturbances, such as movement of the upper layers of the soil as a result of anthropogenic or military operations. Analysis of time sections revealed the asynchrony of soil restoration processes (Table 4). The presented data indicate the phenomenon of heterogeneous recovery, where the rate of degradation of pollutants does not correlate with the rate of recovery of biophysical parameters of the ecosystem. Analysis of the time intervals of 2021-2025 showed a pronounced nonlinearity of processes: while the concentration of petroleum products showed an exponential decrease due to the processes of natural attenuation and microbiological oxidation, other components of the system showed inertia or persistent degradation. Of particular concern is the dynamics of heavy metals, in particular lead (Pb), whose persistence in the soil profile creates the risk of long-term ecotoxicological effects. Although there was a slight decrease in its concentration compared to the peak of 2023, which is probably conditioned by the redistribution of the metal between the soil phases or its leaching into the lower horizons, and not to the actual detoxification of the substrate. The most critical aspect is the state of the humus horizon. A sharp drop in humus content to values below 1% in 2023 signals the destruction of the soil absorption complex. Further recovery to 1.4% in two years is not sufficient for the regeneration of biological activity and aggregate stability of the soil. This state can be defined as the "dissociated reduction" phase, where chemical purification from organic compounds occurs independently of the restoration of the physico-chemical matrix of the soil. This supports the hypothesis that the self-renewal of the soil ecosystem after a complex anthropogenic load is limited. Without targeted phytoremediation and the introduction of structuring agents, the soil remains in a state of functional collapse, where deep structural and biochemical degradation persists at formally acceptable levels of organic contamination.

Table 4. *Dynamics of restoration of various components of the soil ecosystem (2021-2025)*

Type of damage	Status (2021)	Status (2023, model)	Status (2025, data)	Recovery trend
Petroleum products, mg/kg	<1.0	150-250	~10-34	Fast (natural attenuation)
Lead (Pb), mg/kg	<5.0	15-25	~6.7	Very slow (persistence)
Humus, %	2.5-3.0	<1.0	~1.4	Missing (sustained degradation)

Source: compiled by the authors

A comprehensive analysis of the soil cover in the zone of intense military influence on the territory of the Kalynivka village allows characterising the state of the ecosystem as a result of a "toxic cocktail", where the synergistic effect of physical destruction and chemical contamination exceeds the sum of individual negative impacts. Unlike classical models of industrial pollution, the military transformation of sod-podzolic soils is accompanied by a deep inversion of the profile and the destruction of natural defence mechanisms. The observations made are consistent with the conceptual provisions by S.A. Baliuk *et al.* (2024) that military degradation is a multi-factorial process in which mechanical damage acts as a trigger for long-term loss of soil fertility and structural integrity.

The main indicator of systemic soil pathology is catastrophic dehumification: a comparison of empirical data from 2025 with the simulated pre-conflict state revealed a drop in humus content from 2.5-3.0% to an average of 1.4%. This process, described by J.P. Hupy & R.J. Schaetzl (2013) as "bombturbation", leads to physical burning of organic matter and mixing of the humus horizon with iluvial layers. According to N. Kussul *et al.* (2023), such destruction in a war zone is accompanied by a complete loss of stability of soil aggregates. The loss of humus automatically leads to a decrease in the cation exchange capacity, which in conditions of light granulometric composition in the soils of Polissia makes them a transit environment for toxicant migration.

Discussion of the results obtained in the context of global research suggests that the identified changes are sustainable. In particular, O.V. Dmytrenko *et al.* (2023) highlighted the irreversibility of organic carbon loss due to pyrogenic degradation. Current data support this hypothesis, since even three years after the active phase of hostilities, the recovery of the humus layer is minimal. The drop in organic content is accompanied by persistent acidification of the soil solution (pH decreased from 5.8-6.2 to 5.2). According to W. Leal Filho *et al.* (2024), changes in acidity under the influence of pyrogenic factors are a key mechanism that radically increases the mobility of heavy metals.

Special attention should be paid to the vertical distribution of pollutants. The content of chromium (10.02-18.10 mg/kg) and nickel (4.54-8.53 mg/kg) in the selected samples did not exceed the standard MPC, but their distribution was abnormal – the concentrations increased with depth. The Pearson correlation coefficient between depth and chromium content (r ≈ +0.92) mathematically proved the mechanical inversion hypothesis. This is consistent with the findings of K. Petrushka *et al.* (2023), who pointed out that artificial mixing of layers creates new geochemical barriers at atypical depths. The distribution of petroleum products in the profile acted as a unique tracer. The detected peak concentration (66.7 mg/kg) at a depth of 30-40 cm against the background of low content in the upper layer (13.3 mg/kg) is evidence of overlap of the contaminated surface with inverted soil layers. The issue of such "buried" tanks was analysed in detail in the paper by P. Pereira *et al.* (2022), which noted that they act as sources of secondary contamination for decades. Data on mobile forms of nitrogen (26.3 mg/kg), phosphorus (122.4 mg/kg), and potassium (124.6 mg/kg) showed high values against the background of humus deficiency. This condition can be classified as "fragile fertility" – an artificial agrochemical balance that masks the functional collapse of the ecosystem. As noted by I. Bulba *et al.* (2024) in their research, this condition leads to rapid leaching of nitrates into groundwater due to the lack of a sorption complex, which creates risks also described in the paper by B. Biyashev *et al.* (2023). Comparison of recovery dynamics revealed the phenomenon of heterogeneous recovery. If the content of petroleum products showed a tendency to natural attenuation, which is consistent with the findings of M. Solokha *et al.* (2024), humus values and structural characteristics remained consistently low, requiring special reclamation measures.

Thus, the results of the study showed that the military impact caused not just a change in individual indicators, but a complete restructuring of the functioning of the soil system. The results obtained in this study indicate a limited potential for self-renewal of such ecosystems. Without targeted phytoremediation and the introduction of structuring agents, the soil remains in a state of functional collapse, turning from a living system into an inert environment, which becomes only a transit zone for the spread of pollutants to adjacent environments – groundwater and food chains.

Conclusions

A comprehensive study of the transformation of sod-podzolic soils in Kalynivka indicates that military degradation is a multi-factor process, where the dominant factor is physical destruction (bombturbation), which becomes a trigger for a cascade of negative agrochemical and geochemical changes. The main quantitative evidence of systemic destruction of the soil body is the results of correlation analysis: an abnormally high positive relationship (r ≈ +0.92) was established between the depth of occurrence and the concentration of chromium and nickel. This specific stratigraphy, in which metal concentrations increase towards the lower horizons (Cr – from 10.02 to 18.10 mg/kg, Ni – from 4.54 to 8.53 mg/kg), is a direct indicator of mechanical inversion of the profile and "scalping" of the upper layers. Empirical evidence confirmed a catastrophic loss of organic matter: the humus content decreased from pre-conflict 2.5-3.0% to a critical level of 1.4%, indicating deep dehumification due to pyrogenic effects and mixing of genetic horizons. Concomitant acidification of the soil solution (a decrease in pH from 6.2 to 5.2) creates conditions for the transition of heavy metals to mobile, phytotoxic forms. The phenomenon of "fragile fertility" was identified, when locally high values of mobile nitrogen (26.3 mg/kg), phosphorus (122.4 mg/kg) and potassium (124.6 mg/kg) against the background of humus deficiency indicate instability of the agroecosystem and a high risk of leaching nutrients into ground water.

Geochemical analysis of the distribution of petroleum products revealed a "buried" peak of contamination (66.7 mg/kg) at a depth of 30-40 cm, which allows reconstructing the process of burying the contaminated ground surface under emissions from sinkhole formations. A state of "dissociated reduction" was established, in which relatively rapid self-purification from organic pollutants contrasts with stable physical destruction and lead persistence (Pb ~6.7 mg/kg). This proves that the natural recovery potential of the affected land is limited. Recovery strategies should be based not only on detoxification, but primarily on restoring the physical architectonics of the soil and restoring its biochemical buffering through intensive humification.

Further research should be aimed at developing dynamic models for predicting the migration of toxicants from "buried" layers of pollution to underground horizons. It is also necessary to investigate the effectiveness of various types of phytoremediants and microbial preparations for accelerated restoration of the humus state of soils that have undergone mechanical inversion.

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Conflict of Interest

None.

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Трансформація ґрунтового покриву під впливом воєнної агресії: інтегрована оцінка на прикладі Київського Полісся

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Анотація. Військові дії значно впливають на ґрунтовий покрив, що має серйозні наслідки для екології та продовольчої безпеки. Метою дослідження було проаналізувати зміни в агрохімічних та геохімічних характеристиках ґрунтів внаслідок військових дій 2022 року в Україні. Дослідження фокусувалось на території села Калинівка Фастівського району Київської області на дослідній ділянці місця виливу нафтопродуктів. На основі порівняння емпіричних лабораторних даних (2024 р.) – з модельованими станами доєскалаційного періоду (2021 р.) та періоду гострого впливу (2022 р.) – розкрито багатофакторний характер воєнного впливу на деградацію ґрунтів. Встановлено, що домінуючим фактором руйнування є не хімічна контамінація, а глибоке фізичне порушення ґрунтового профілю: інверсія горизонтів, ущільнення та «скальпування» родючого шару, що сукупно описується терміном «бомботурбація». Проведено детальний кореляційний аналіз, який кількісно підтвердив гіпотезу інверсії: виявлено сильну позитивну кореляцію ($r \approx +0.94$) між глибиною та концентрацією важких металів (Cr), що є аномальним для природних умов. Це явище, разом із критично низьким вмістом гумусу та аномальним розподілом нафтопродуктів, свідчить про поховання початково забрудненої денної поверхні. Аналіз часової динаміки виявив феномен «роз'єднаного відновлення», за якого швидка біодеградація органічних полютантів контрастує зі стійкістю фізичних пошкоджень та забруднення важкими металами. В роботі підкреслено, що ігнорування фізичної складової деградації та спроби ведення сільського господарства за традиційними схемами неминуче призведуть до посилення екологічних ризиків та подальшої втрати аграрного потенціалу. Результати дослідження можна використати для розробки стратегій відновлення ґрунтів на постраждалих територіях України, що сприятиме зниженню екологічних ризиків і відновленню аграрного потенціалу

Ключові слова: деградація ґрунтів; воєнний конфлікт; бомботурбація; важкі метали; нафтопродукти; інверсія профілю; кореляційний аналіз