UDC 631.4:504.054:631.618(477)
DOI https://doi.org/10.32782/2226-0099.2026.148.2.18

POST-WAR SOIL RESTORATION IN UKRAINE: PROSPECTS AND CHALLENGES

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The article examines the problem of post-war soil restoration in Ukraine under conditions of large-scale contamination and physical damage caused by hostilities. The relevance of the topic is determined by the fact that the war has affected extensive areas of agricultural land through UXO and explosive contamination, localized chemical pollution, petroleum products, munition fragments, combustion residues from destroyed military equipment and direct mechanical disturbance of the soil profile. For Ukraine, this issue has a special significance because the high share of agricultural land in the national territory directly links soil condition with food security, economic recovery, the stability of rural areas and environmental safety. The article summarizes international and Ukrainian data on the scale of land contamination and reviews field studies that recorded elevated concentrations of heavy metals in soils collected from war-affected sites. It is shown that humanitarian demining is a necessary but insufficient condition for returning land to safe use. Even after explosive hazards and UXO have been removed, some plots may remain only partially suitable because of explosive residues, petroleum products and structural degradation of the soil. The article proposes a staged approach to land restoration, icluding the identification and mapping of damaged areas, agrochemical and toxicological testing, risk based zoning, the choice of suitable remediation methods, and follow up monitoring after the works are performed. Further research could focus on the development of matrix based field survey schemes for damaged land, criteria for classifying soil suitability and practical models for choosing between local remediation, phytoremediation and temporary or permanent withdrawal of land from agricultural use.

Key words: *soils, soil contamination, post-war restoration, remediation, phytoremediation, agricultural land, humanitarian demining.*

Мельниченко В.В. Післявоєнне відновлення ґрунтів в Україні: перспективи та виклики

Стаття присвячена проблемі післявоєнного відновлення ґрунтів в Україні в умовах широкомасштабного забруднення та фізичного пошкодження земель, спричинених бойовими діями. Актуальність теми зумовлена тим, що внаслідок війни значні площі сільськогосподарських угідь опинилися під впливом мінного та вибухонебезпечного забруднення, локальних осередків хімічного ураження, нафтопродуктів, уламків боєприпасів, продуктів згоряння військової техніки та механічного порушення ґрунтового профілю. Для України ця проблема має особливе значення, оскільки висока частка сільськогосподарських земель у структурі території країни прямо пов'язує стан ґрунтів із продовольчою безпекою, відновленням економіки, стабільністю сільських територій та екологічною безпекою. У статті узагальнено дані міжнародних і українських джерел щодо масштабів забруднення земель, а також проаналізовано результати окремих польових досліджень, у яких зафіксовано перевищення фонових значень за вмістом важких металів у ґрунтах на територіях, що зазнали бойового впливу. Показано, що гуманітарне розмінування є необхідною, але недостатньою умовою для повернення землі у безпечне використання. Навіть після вилучення вибухонебезпечних предметів ділянки можуть залишатися обмежено придатними через наявність залишків вибухових речовин і нафтопродуктів, а також через

структурну деградацію ґрунту. Обґрунтовано доцільність поетапного підходу до відновлення земель, який передбачає картування пошкоджених ділянок, агрохімічне й токсикологічне обстеження, зонування ризиків, вибір технологій ремедіації та подальший моніторинг. Окрему увагу приділено фіторемедіації як одному з інструментів відновлення для тих ділянок, де рівень забруднення дозволяє застосовувати екологічно безпечні та економічно реалістичні методи очищення. В статті зроблено висновок, що ефективна система післявоєнного відновлення ґрунтів має поєднувати результати протимінної діяльності, дані лабораторного контролю, науковий супровід і механізми державного управління. Перспективним напрямом подальших досліджень вбачається розроблення матричних схем польового обстеження пошкоджених земель, критеріїв класифікації придатності ґрунтів та практичних моделей вибору між локальною ремедіацією, фіторемедіацією і тимчасовим виведенням земель з господарського обігу.

Ключові слова: *ґрунти, забруднення ґрунтів, післявоєнне відновлення, ремедіація, фіторемедіація, сільськогосподарські землі, гуманітарне розмінування.*

Problem statement. The full-scale war has caused a long term land use problem in Ukraine. Its visible part is mine contamination and explosive remnants of war. Its less visible part is the deterioration of soil quality after explosions, burning military equipment, debris deposition, fuel spills, repeated shelling and severe mechanical disturbance of the surface layer. These processes affect the possibility of safe agricultural use even after a site has been cleared of explosive hazards through demining.

The scale of the problem is considerable. According to the ACAPS thematic report on the humanitarian implications of mine and UXO contamination in Ukraine, ten percent of agricultural land was contaminated, which prevented the sowing of about five million hectares [1, p. 1]. The rapid damage and needs assessment for Ukraine states that around 174,000 km² of territory may be contaminated by explosive ordnance [3, p. 182]. For Ukraine where agricultural land occupies 70.5% of the territory and arable land reaches 57%, with higher shares in some regions, the issue of soil restoration goes far beyond environmental policy and directly concerns food production, export capacity, rural employment and local budget recovery [2, p. 7].

In this context, post-war soil restoration should be seen as a practical priority, not as a secondary aspect of demining.

An agricultural field can be physically accessible and formally cleared, but still remain unsafe or economically unsuitable for agricultural use because of soil chemical contamination or severe local degradation.

Analysis of recent research and publications. Existing publications on war-related environmental damage in Ukraine can formally be divided into three groups:

– mine action and the humanitarian consequences of contamination;
– environmental losses caused by the war, including damage to land resources;
– field studies that document soil pollution and specific changes in affected territories.

International analytical materials already confirm that land contamination has become one of the central constraints on the recovery of rural areas. The ACAPS report connects mine contamination with disrupted access to agricultural land and reduced production [1, p. 1]. The RDNA3 report frames UXO contamination as a nationwide challenge with long-term consequences for recovery planning [3, p. 182-184]. The report on the environmental consequences of the war in Ukraine also outlines the substantial weight of agricultural land in the national land-bank structure, which means that the degradation of soils has consequences for the whole economy, not only for local ecosystems [2, p. 7].

At the level of direct soil studies, the article by Yu. O. Zaitsev et al, deserves particular attention. The authors investigated soils from the Sumy and Okhtyrka districts

of Sumy region and found significant exceedances above background values for a number of heavy metals, especially at sites affected by explosions and destroyed military equipment [4, p. 136, 142, 147]. These results are consistent with the earlier OSCE-supported assessment of eastern Ukraine, where shelling sites demonstrated concentrations of some heavy metals above background values and where crater zones were identified as local points of intensified soil disturbance [7, p. 13; 7, p. 35].

At the same time, the literature available so far does not adequately cover this issue. Many articles describe contamination as a fact, but much fewer propose an operational sequence that begins after demining and leads to a reasoned decision on whether a field can be returned to agricultural use, on what terms and after which treatment.

Under the current conditions in Ukraine, several practical issues still require further development. There is still no widely adopted algorithm that links the completion of humanitarian demining with mandatory agrochemical and toxicological assessment. In the same time damaged agricultural land is rarely classified by degrees of suitability in a way that would help land users and public authorities decide between immediate cultivation, limited use, remediation, or temporary withdrawal. The selection of remediation methods is often discussed in general terms, while field conditions can vary considerably even within a single plot. A field can include crater bottoms, crater rims, burned vehicle locations, tracks of heavy equipment, debris accumulation zones and areas that appear visually intact. Standard agricultural sampling may miss local peaks of contamination if it is not adapted to the geometry of war-related disturbance. This raises the need for matrix-based or zone-based field survey schemes that are tied to the types of visible damage.

The management side is also not sufficiently developed. Mine action data, lab data and land use decisions are often stored and processed in separate institutional systems. Without an integrated chain from clearance to environmental assessment and land status assignment, the recovery process remains slow and ineffective.

Purpose of the study. The purpose of the study is to summarize the main challenges of post-war soil restoration in Ukraine and to identify the principal forms of soil damage and contamination caused by war while substantiating a practical sequence of actions for assessing and restoring agricultural land after hostilities.

Materials and methods of research. This study is based on an analytical and interdisciplinary approach to assessing the problem of post-war soil remediation in Ukraine. The research combines methods of environmental analysis, comparative review, systematization of scientific sources and synthesis of available empirical data on war-related soil contamination.

The material base of the study includes analytical reports of international organizations, official documents of Ukrainian state agencies and institutions, strategic documents in the field of mine action and published scientific papers devoted to soil contamination caused by military-related activity. Particular attention was given to sources providing empirical data on the scale of land contamination, the impact of explosive remnants of war on agricultural areas and the recorded presence of heavy metals and petroleum products in soils.

The methodological basis of the article based on several interconnected methods:

1. The method of analysis and generalization, which was used to identify the main types of war-related impacts on soils, including mechanical disturbance, chemical contamination and long-term ecological degradation.\

2. The comparative method, which was applied to compare different groups of sources, including policy documents, field-based environmental assessments and scientific studies of contaminated agricultural lands in Ukraine.

3. The system approach, which was used to examine post-war soil restoration as a sequence of interrelated stages that includes site identification, demining, environmental assessment, sampling, risk zoning and selection of remediation measures and monitoring of remediated land.

The study also applies an element of qualitative risk-oriented assessment. Within this approach, war-affected land is considered not as a homogeneous object, but as a spatially differentiated system where the degree and type of damage may vary within the same land plot. This makes it possible to justify the need for differentiated sampling, local assessment of contamination areas and the selection of remediation actions according to the actual condition of the soil.

The method of conceptual modelling allowed to suggest structured framework for post-war soil restoration, which bridges humanitarian demining with subsequent agrochemical, toxicological and ecological assessment. Such an approach allows the restoration process to be considered not only as a technical response, but also as a broader environmental and land-management policy.

Presentation of the main research material. War affects soils through several mechanisms that often act simultaneously. One of them and the most common is a mechanism of mechanical disturbance. Explosions create craters, mix soil horizons, destroy aggregate structure, change local drainage and remove part of the humus-rich topsoil. The movement of heavy military equipment compacts the soil, reduces porosity, worsens aeration and can create long strips of degraded land that remain visible after the end of active hostilities. These impacts reduce water infiltration and root penetration and may lower the productive capacity of the field even where chemical contamination levels are not substantial.

Another mechanism is chemical contamination. Explosions and combustion release residues of energetic materials, hydrocarbons, metals, soot, products of incomplete burning and its mixes. Destroyed vehicles and machinery add wide range of petroleum products, lubricants, plastics and metals to the site. As a result, the agricultural field becomes not just a mined area, but also a chemically polluted environment. In the study from Sumy region, three soil samples were taken from bomb craters and seven from sites with destroyed heavy armored vehicles. The authors recorded exceedances above background values for lead, copper, zinc and manganese. Lead showed the most visible increase and the highest levels of disturbance were associated with burned or destroyed military equipment [4, p. 136, 142, 147]. Available assessment materials for eastern Ukraine also showed systematic exceedances above background values for a number of elements and indicated that crater areas can accumulate heavier contamination loads [7, p. 13; 7, p. 25; 7, p. 35].

There is also another mechanism that plays an important role in assessing ecological degradation resulting from the interaction of physical and chemical factors. Soil biota responds to the presence of toxic elements and hydrocarbons, while plant growth is limited by compaction, altered aeration and local toxicity. This means that the same plot may show both direct contamination and indirect loss of soil fertility. From a land management perspective, this is important because agricultural suitability depends not only on whether contamination exceeds a laboratory threshold, but also on whether the soil is able to perform its productive and ecological functions.

These observations explain why post-war demining is only the first step. The National Mine Action Strategy of Ukraine recognizes the need to minimize the environmental effects of explosive ordnance contamination and to incorporate such risks into recovery management [5, p. 23-24]. The current scale of work also shows the existing challenge.

According to the report of the State Special Transport Service, 187,043 explosive ordnance items had been disposed of, and more than 128,265 hectares had been covered by non-technical survey and clearance. The reported breakdown includes:

– 0.26 km² of water bodies;
– 914 km of automobile roads;
– 2,639 km of railways;
– 493 km of power lines;
– 82 km of pipelines;
– 374 ha of residential areas;
– 115,749 ha of agricultural land [6, p. 5].

These efforts are indispensable, but they do not provide a complete answer to the question of whether a given agricultural site is ready for safe use. For this reason, post-war soil restoration should be organized as a phased procedure;

First stage– damaged sites identification and mapping. This includes crater locations, burned vehicle positions, suspected zones of fuel leakage, debris concentration and disturbed access routes. The result of this stage should not be a generic note that the field was affected by hostilities, but a spatial scheme of likely risk points.

Second stage– sampling and laboratory assessment. In war-affected fields, sampling should be adapted to the morphology of damage. A rational design includes at least the crater bottom, the crater wall or rim, a nearby surrounding zone and a background point outside the visible damage contour. For burned equipment sites, separate samples should be taken from the center of the burn zone, the runoff direction if visible and the adjacent unaffected soil. Such differentiation is necessary because average field sampling can smooth out local contamination peaks.

Third stage– site classification by degree of suitability. In practical terms it can be categorized under four categories: land suitable for use without restrictions; land suitable after local measures; land requiring medium-term remediation; and land temporarily unsuitable for agricultural use. The logic of such classification is that it converts laboratory results into decisions that can be used by landowners, farmers, local authorities and recovery programs operators.

Fourth stage– remediation methods selections. It should be considered that there is no universal method for all cases. Where contamination is highly localized, local excavation or isolation of the polluted layer may be applied. Where hydrocarbons dominate, bioremediation may be effective. Where contamination levels are moderate and large areas are involved, phytoremediation is seen as the most practical, effective and cost-saving solution. It is slower than mechanical replacement of soil, but it is much more realistic for broad agricultural territories.

It is worth mentioning that phytoremediation is appealing for a number of practical reasons. It does not require aggressive disturbance of the soil body, it can be implemented on large areas and it fits the logic of gradual ecological recovery. It is especially relevant for sites where the contamination level does not justify full removal of soil, but still prevents the immediate return of land to agricultural use and food production. At the same time, phytoremediation should not be seen as a universal solution. This requires the precise selection of a remediating plant species that, under the given conditions, can most effectively extract contaminants from the soil, time, control over biomass handling and repeated monitoring. In practice, it is best treated as one element within a combined restoration program rather than as a stand-alone solution.

A separate issue concerns the institutional side of restoration. A land plot should not move directly from the status of "cleared" to the status of "ready for cultivation"

without an intermediate environmental check. The current gap between mine action records, laboratory information and land management decisions creates a risk of premature return to use. A more rational system would include a sequence such as:

– completion of clearance;
– primary environmental screening;
– laboratory testing and confirmation;
– assignment of land suitability status;
– post-remediation monitoring;

This sequence would reduce uncertainty and support more defensible decisions both for agricultural producers and at the level of public policy.

Conclusions and prospects for further research. The war in Ukraine has highlighted that the post-war soil restoration should be considered as a separate and urgent field of practical work as well as incorporated into public policy. The core nature of Practice shows that damage to agricultural land is usually multifaceted and is caused not only by explosive hazards, but also by a combination of other factors, such as mechanical disturbance, heavy metal contamination, combustion residues, petroleum products, and local functional degradation of the soil. Given the scale of agricultural land in Ukraine, this problem directly affects food security, export capacity, rural recovery and environmental safety [1, p. 1; 2, p. 7; 3, p. 182].

Available field data already show that war-affected soils may contain concentrations of heavy metals above background values, especially in crater zones and at sites of burned military equipment [4, p. 136, 142, 147; 7, p. 13; 7, p. 35]. This confirms the assumption that humanitarian demining, while essential, does not by itself return land to safe productive use. In view of the above, a scientifically grounded recovery model should be based on a phased and standardized approach, allowing decisions to be made on whether contaminated land should be restored or removed from agricultural use for a specified period.

Considering the scale of the problem and the long-term consequences of soil contamination, there is a clear need in Ukraine for a more coherent transition from mine action to soil assessment and land-use decision-making. Matrix-based survey schemes for damaged fields, criteria for classifying land suitability and applied models for choosing between methods of rapid response appear to be the most important directions for further research. Such work would strengthen the evidence base for post-war agricultural recovery and would make the return of land to use safer and economically feasible.

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Дата першого надходження статті до видання: 02.04.2026
Дата прийняття статті до друку після рецензування: 01.05.2026
Дата публікації (оприлюднення) статті: 22.05.2026