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ANTHROPOGENIC LOAD ON SOIL RESOURCES IN WAR CONDITIONS AND DIRECTIONS FOR THEIR RESTORATION

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Armed conflicts and wars cause extensive damage to the environment, in particular causing serious pollution of soil and water resources. Military operations are accompanied by explosions, shelling and destruction of critical infrastructure and industrial facilities, leading to the release of toxic substances into the environment. The use of chemical, biological or nuclear weapons poses a particular threat, significantly complicating the subsequent restoration of natural ecosystems. In addition, enterprises located in temporarily occupied territories may release hazardous chemical compounds into the atmosphere without proper control.

As a result of Russia's full-scale aggression against Ukraine, a significant part of the country's land fund has suffered catastrophic destruction. This scientific paper presents an analytical review of literary sources on the subject of the study. The main types of land pollution caused by military operations are systematized, among which mechanical, physical, chemical and biological factors are highlighted. The environmental damage caused by the war is analyzed, and recommendations are made for the revitalization of degraded land and the restoration of its fertility. It is emphasized that the process of soil restoration after military action is complex, long-term and requires the consolidated efforts of the state, the scientific community, international organizations and land users. For an objective assessment of damage and losses, the Ministry of Environmental Protection and Natural Resources of Ukraine approved the Methodology for determining the extent of damage caused to land and soil as a result of emergencies, armed aggression and hostilities during martial law.

Key words: land pollution, military action, mechanical pollution, physical pollution, chemical pollution, biological pollution, restoration.

Бойко М.О. Антропогенне навантаження на ґрунтові ресурси в умовах війни та напрямки їх відновлення

Збройні конфлікти та війни завдають масштабної шкоди навколишньому середовищу, зокрема спричиняють серйозне забруднення ґрунтів і водних ресурсів. Проведення військових операцій супроводжується вибухами, обстрілами та руйнуванням критичної інфраструктури й промислових об'єктів, що призводить до потрапляння токсичних речовин у довкілля. Особливу загрозу становить застосування хімічної та біологічної зброї, що значно ускладнює подальше відновлення природних екосистем. Крім того, підприємства, розташовані на тимчасово окупованих територіях, можуть викидати небезпечні хімічні сполуки в атмосферу без належного контролю. У контексті аграрного виробництва зазначені екологічні наслідки воєнних дій безпосередньо впливають на зниження продуктивності земель, погіршення якісних характеристик сільськогосподарських угідь та зростання витрат виробників на відновлення родючості ґрунтів. Це, своєю чергою, посилює економічні ризики для аграрних підприємств, впливає на собівартість продукції та формує додаткові виклики для забезпечення продовольчої безпеки й сталого розвитку аграрного сектору України.

Унаслідок повномасштабної агресії росії проти України, значна частина земельного фонду країни зазнала катастрофічного руйнування. У даній науковій роботі представлено

аналітичний огляд літературних джерел за тематикою дослідження. Систематизовано основні типи забруднення земель спричинені бойовими діями, серед яких виокремлено механічні, фізичні, хімічні та біологічні чинники. Аналізовано екологічні збитки, завдані війною, а також запропоновано рекомендації щодо ревіталізації деградованих земель і відновлення їх родючості. Наголошено, що процес відновлення ґрунтів після воєнних дій є складним, довготривалим і вимагає консолідованих зусиль держави, наукової спільноти, міжнародних організацій та землекористувачів. Для об'єктивної оцінки руйнівних наслідків та втрат Міністерством захисту довкілля та природних ресурсів України було затверджено Методику визначення розміру збитків, завданої землі та ґрунтам внаслідок надзвичайних ситуацій, збройної агресії та бойових дій під час воєнного стану.

Ключові слова: забруднення земель, воєнні дії, механічне забруднення, фізичне забруднення, хімічне забруднення, біологічне забруднення, відновлення.

Problem statement. Fertile soil is an extremely important element for agricultural production, and its importance cannot be overestimated. It provides plants with the necessary nutrients, and the diversity of minerals and organic substances in the soil allows plants to obtain all the elements necessary for growth and development. The ability of soil to retain moisture and supply it to plants determines its importance for growing crops. Soil provides support for the root system of plants, ensuring their stability and ability to obtain the necessary substances. The top layer of soil supports a variety of microorganisms, which in turn affects biodiversity as a whole. It is a natural barrier that protects against erosion, preventing the soil cover from being washed away by water or wind. Most importantly, soil is the basis for growing plants, which are the foundation of food production.

Ukraine's agricultural sector has been hardest hit by the war unleashed by the Russian Federation, as the fighting is mainly taking place on the fields of Ukrainian enterprises and farms. In addition, there is a very serious problem of contamination of fertile land with detonated or unexploded ordnance, mines and spilled petroleum products. According to international experts, the total area of mined territories in Ukraine at the end of 2022 was 174,000 square kilometers, which is twice the size of Austria. In 2024, the area of potentially mined land decreased by more than 20% compared to the end of 2022 due to demining and amounted to about 137,000 square kilometers [1].

Threats to soils – in particular their destruction as a result of military action, pollution or unsystematic use – can significantly reduce their productivity, which negatively affects agricultural production, food security and the ecological stability of the state. Soils regenerate extremely slowly: it takes about 100 years for just one centimeter of fertile soil to regenerate naturally. Restoring soil cover and associated ecosystems requires a long time and coordinated action. It is necessary to develop strategies today that will accelerate the rehabilitation of Ukrainian black soil after the war. Soil conservation and protection must become a priority to ensure the sustainable development of the agricultural sector.

Analysis of recent research and publications. The armed aggression of the Russian Federation against Ukraine, which began in 2014, has had a significant and lasting negative impact on the natural environment, causing profound ecological changes. The relevance of the problem of restoring soil fertility in the post-war period is actively considered by both Ukrainian and foreign scientists. In particular, Y.O. Zaitsev and co-authors investigate the environmental risks caused by hostilities on the territory of Ukraine and present the results of an experimental analysis of the content of gross forms of heavy metals in agricultural soils of the Sumy and Okhtyrka districts of the Sumy region [2]. In turn, Balyuk S. and Kucher A. focus on the need to adapt state land policy in the context of martial law and post-war recovery, emphasizing the importance of

improving regulatory and legal regulation in the field of land use and protection. They pay particular attention to the development of effective mechanisms for soil protection and restoration of its fertility, particularly in areas damaged by armed conflict [3].

Kravchenko O. and co-authors investigate key factors causing pollution and degradation of environmental components as a result of military actions in eastern Ukraine. In their research, the authors emphasize that armed conflict has a devastating impact on all elements of the environment without exception. In order to objectively determine the extent of damage caused and the degree of pollution of the territories, it is necessary to conduct systematic environmental monitoring and develop a comprehensive programme of measures to restore the natural environment [4].

In her scientific research, Lisova N. thoroughly analyses the environmental consequences of military actions, based on the results of studies conducted by the International Charitable Organization 'Ecology – Law – Man' and the Eastern Ukrainian Ecological Institute. Particular attention is paid to the impact of military conflict on the fertility of agricultural land. The author highlights a wide range of environmental problems, including the negative impact of groundwater due to the flooding of mines and their emergence on the surface, the destruction of purification systems, chemical and radiation contamination of water bodies, pollution of the atmosphere and soil, as well as landscape degradation, destruction of vegetation cover and significant forest areas [5].

The scientific works of Weber A.K. and co-authors investigate the chemical impact of military operations on the transformation of the natural properties of soil cover under the influence of pollutants formed as a result of the use of various types of weapons and military equipment. It is noted that prolonged warfare leads to the formation of local military-technogenic geochemical anomalies, characterized by the presence of a wide range of explosive and toxic substances. Such areas may be unsuitable for agricultural or other use for an indefinite period [6].

Research by Takahashi, K. *et al.* has shown that one of the key mechanical effects of military operations on the soil is its compaction with disruption of the humus horizon, which leads to significant negative consequences, in particular, disruption of the soil water regime and intensification of water and wind erosion processes. Military and technogenic loads cause mechanical deformation of the soil cover, which occurs as a result of the movement of wheeled and tracked military equipment, troop movements, the construction of fortifications, bombing, demining and clearing of territories from ammunition remnants [7].

Gillies, J.A. *et al.* in their studies consider the main forms of physical soil pollution, in particular vibration, radiation and thermal effects. The authors note that local temperature increases occur due to emissions of heated air, powder gases, gaseous combustion products, and exhaust gases, which together cause a decrease in biodiversity in ecosystems [8].

At the same time, the war has a significant impact not only on the natural environment of Ukraine, but also on the socio-economic and environmental systems of many countries around the world, which necessitates further interdisciplinary scientific research. An important issue remains unresolved today: the lack of clearly formulated practical solutions and specific measures aimed at minimizing risks to agricultural production in conditions of soil degradation caused by military actions.

Research objective. The aim of this study is to provide a comprehensive scientific justification of the nature and consequences of anthropogenic pressure on soil resources in conditions of military action, particularly in the context of armed aggression on the territory of Ukraine, as well as to identify priority areas for their restoration.

Presentation of the main research findings. Soil is a key independent element of the biosphere and the natural environment, which is at the same time a limited, difficult to restore and irreplaceable resource. It performs a number of critically important functions: productive (biomass and food production), ecological (biogeochemical, hydrological, gas exchange, etc.), social and informational. Today, the issues of soil conservation, rational use and protection, as well as combating soil degradation, have become globally significant [9].

Although the environmental consequences of war often remain overlooked due to the focus on human casualties and infrastructure destruction, changes in the physical and chemical properties of soils are long-lasting and significantly reduce their ecosystem productivity. Military actions have a multi-vector impact on the soil environment: from contamination with toxic substances (explosives, combustible materials, chemicals) to physical degradation, compaction and erosion. The destruction of infrastructure (in particular, oil pipelines) leads to large-scale soil contamination with petroleum products.

Since 24 February 2022, full-scale war in Ukraine has caused significant damage to soil cover across large areas. The assessment of military and man-made stress is carried out taking into account the intensity of hostilities and types of pollution. The consequences also include loss of vegetation, degradation of ecosystems, pollution of water bodies, and disruption of biodiversity. The restoration of soils and associated natural systems in de-occupied territories will require considerable time and coordinated efforts to return to a sustainable ecological state (Fig. 1).

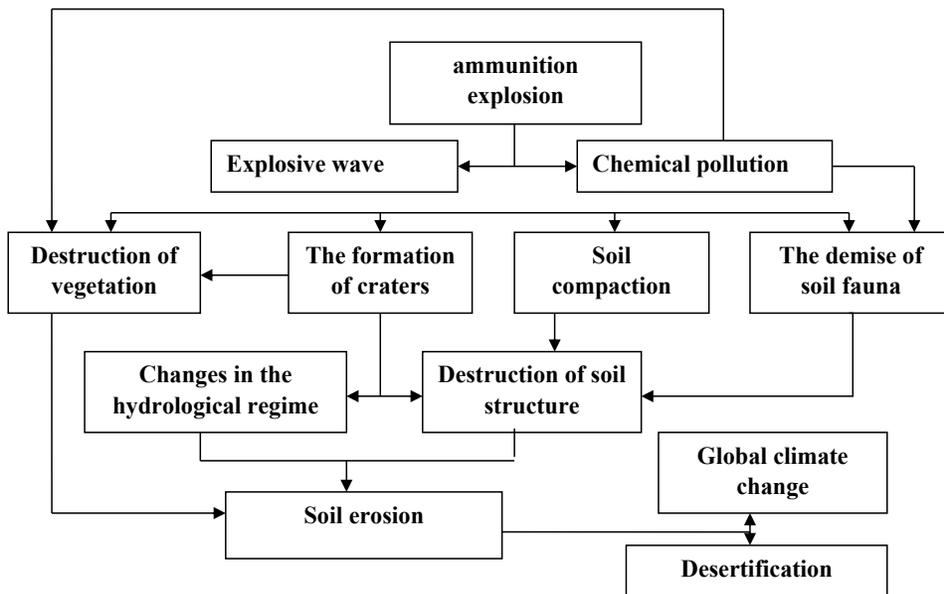


Fig. 1. Soil contamination from explosives

Source: [10]

Soil contamination resulting from military operations can be mechanical, physical, chemical, or biological. Each of these types of damage is critical in its own way and causes disruption to the structure and functions of the soil. Let us examine each type of damage in more detail [11].

Mechanical soil contamination consists of the deformation of the soil cover and the destruction of its structures as a result of intense anthropogenic impact, in particular the movement of military equipment and personnel, the construction of engineering fortifications, aviation and artillery shelling, as well as demining processes. These actions cause soil compaction, waterlogging in low-lying areas, local erosion, and surface contamination with ammunition remnants, scrap metal, and combustion products.

The key mechanical consequence is the compaction and degradation of the humus layer, leading to disruption of the soil water regime, reduced air and water permeability, and loss of agronomically valuable structure. As a result of the movement of soil particles between the fertile horizon and the lower layers, the structure becomes dispersed, which increases the risk of wind and water erosion. Demining, as one of the most destructive mechanical impacts, is often accompanied by the removal or mixing of the humus layer, which leads to the loss of the soil's physical and chemical properties, changes in its granulometric composition, and a decrease in its water-holding capacity. All this together reduces soil fertility and makes it impossible to use it effectively for agriculture without long-term recultivation.

Chemical contamination of soils is accompanied by changes in their physical and chemical properties, in particular the reaction of soil solution (pH), cation exchange potential and organic matter content, especially humus. At the same time, there is an increase in the concentration of toxic chemical compounds, leading to the formation of local landscape and geochemical anomalies. The main sources of such pollution include petroleum product residues (fuel, lubricants), solvents, chemicals, decontaminants, explosive components, combustion products, as well as heavy metals (lead, cadmium, copper, zinc, arsenic) and radionuclides. These elements can be mobile in the soil environment, migrating into aquifers and entering food chains.

The presence of such substances in the soil leads to its toxicity, reduced biological activity, disruption of the microbiological balance and reduced fertility. In the long term, this makes it impossible to use contaminated land for agricultural production without comprehensive remediation and restoration (melioration) measures. Heavy metals serve as indicator components for environmental monitoring of areas affected by military operations, as they have a long retention period in the soil environment and high ecotoxicity.

Physical contamination of soil encompasses changes in its physical characteristics caused by combat operations and the use of military equipment. The main factors of this type of impact are vibration loads, radiation exposure and thermal effects caused by explosions, the movement of heavy equipment, and thermal processes during fires and ammunition explosions. The accumulation of these factors causes profound degradation of the soil profile. The soil's buffer capacity to neutralize external influences is reduced, the aggregate structure is destroyed, the humus layer is lost, and the heat and moisture retention capacity is reduced, leading to a significant decrease in the natural fertility of the soil.

In areas of physical contamination, disturbances in temperature, changes in density, porosity and thermal conductivity may occur, which negatively affect the microbiota, plant development and the stability of the landscape as a whole. The soil's ability to self-regenerate in such conditions is significantly reduced or completely lost, especially in the presence of accompanying chemical and biological factors.

Biological soil contamination involves the degradation or complete destruction of living organisms inhabiting the soil environment, in particular soil microflora, which is key to maintaining biological balance, humus formation, nitrogen fixation, mineralization of organic residues and soil fertility formation. The main factors causing biological

depletion are: soil compaction, which limits oxygen access to microorganisms and root systems; thermal shock caused by explosions or hot materials, which changes the temperature of the environment to a lethal level for biota; mechanical destruction of the soil profile, which disrupts the natural structure and microecosystems; contamination with toxic substances, including heavy metals, explosive residues, petroleum products or chemical reagents, which inhibit the vital activity of microorganisms or destroy them completely. As a result of such impacts, the soil loses its ecosystem functions, including its ability to self-regenerate, its productivity and its participation in biogeochemical cycles. The types of soil contamination resulting from military operations are listed in Table 1.

Table 1

Types of soil contamination resulting from military operations

Type of pollution	Description	Example	Consequences / Analysis
Mechanical	Physical destruction of soil structure, compaction, erosion	Tanks and heavy equipment passed through arable land in the Chernihiv region	Loss of fertile layer, deterioration of water and air permeability, reduction in crop yields
Physical	Debris, rubbish, artificial materials	Shell fragments and equipment in the fields of Kharkiv region	Complications in agricultural work, surface contamination, danger to people
Chemical	Toxic substances entering the soil: explosives, fuel, heavy metals	After the explosion of warehouses in the Kherson region	Contamination of the 'soil-water-food' chain, health risks, long-term degradation
Biological	Contamination by corpses, pathogens, decay products	Improper burial of bodies in Donetsk region	Contamination of aquifers, spread of infections, biological hazard

Source: compiled by the author

The most dangerous in the long term are chemical contaminants, as their effects persist for years and are difficult to eliminate without extensive remediation. The most common in combat zones are mechanical and physical contaminants, as every shelling or movement of equipment leaves direct traces on the ground. The least controllable are biological contaminants, as they are difficult to detect in time and pose a threat of disease outbreaks.

Thus, each of the above types of pollution caused by military actions leads to the destruction of vegetation, soil fertility disruption, natural moisture deficiency, and desertification. As a result, the level of biota is also rapidly declining.

In early June 2025, the Ministry of Environment reported that the total damage to the environment caused by Russian aggression already amounted to 3.9 trillion hryvnias. It is noted that these figures are constantly being updated due to the Russian Federation's ongoing attacks on Ukraine. These figures only take into account the controlled territory of Ukraine, as it is difficult, and sometimes impossible, to assess the damage in the occupied territories [12].

Today, scientists must make every effort to study the impact of war on soil fertility and provide recommendations for restoring the fertility of Ukrainian black soil. The main methods for restoring contaminated soils are:

- Removal of contaminated soil layers;
- Use of plants to fix and reduce the mobility of pollutants;
- Use of filtration systems and chemical methods of water purification;
- Restoration of river ecosystems and biodiversity;
- Use of special chemicals to neutralize toxic substances;
- Thermal production to destroy biologically hazardous substances;
- Planting of plants that can clean the soil (phytoremediation).

According to World Bank estimates, the cost of demining one square meter in Ukraine can be as high as \$8. Based on these forecasts, more than \$37 billion will be needed for demining Ukraine over the next decade alone. At the same time, measures to restore soil fertility are also expensive. To speed up this process, land conservation (the procedure for which is defined in Government Resolution No. 35 of 19 January 2022) and recultivation are used. Reclamation means active soil cleaning using technical and biotechnological measures. These measures are very expensive. The Ecoaction report cites the following data, for example:

- soil phytoremediation (i.e., treatment with plants that reduce the concentration of the pollutant or absorb it): costs from \$150 to \$250,000 per hectare;
- chemical leaching (washing): costs from \$30 to \$300 per cubic meter of soil;
- chemical oxidation/reduction: costs from \$200 to \$500 per tons of treated soil, excluding the cost of analytical studies;
- waste disposal (burying it underground in specially created pits, abandoned coal mines, etc.): costs from \$1 million per tons [13].

Financing reclamation measures requires a comprehensive approach that takes into account the interests of all stakeholders. The use of convenient and effective methods, cooperation between different sectors of society, and government incentives can help overcome financial difficulties and ensure the successful reclamation of Ukrainian land [14-16].

Conclusions. In our study, we paid considerable attention to various types of soil contamination resulting from military operations and methods of soil remediation: these can be artificial or natural. Artificial and natural methods have their advantages and disadvantages, and the justified choice of one method or another may depend on specific conditions and financial capabilities. There are many ways to revitalize soil: remove and dispose of contaminated soil; wash the soil with substances that can destroy contamination; plant plants that can absorb contamination and cleanse the soil. Each method has its own areas of application and weaknesses. Financial resources are important if some methods are too expensive, and it may be necessary to look for more cost-effective solutions. It may also be useful to consider partnerships with government or international organisations, as well as involving the public and local initiatives to support remediation projects.

Another method is conservation, which involves temporarily halting economic activity on the land and is an important tool for restoring and preserving ecosystems. This approach allows nature to recover on its own and restore soil fertility. It is important that conservation is part of a strategic plan for sustainable land management and nature conservation. Such an approach can take into account environmental, social and economic aspects to achieve a balance between use and conservation of nature.

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