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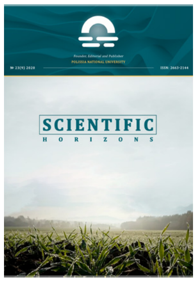

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Identification and monitoring of agricultural land contaminated by military operations

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Abstract. Russia's attack on Ukraine has caused widespread contamination of agricultural land, which is now an urgent environmental problem that is important for human health and sustainable development. In this regard, the purpose of this study was to analyse the impact of military operations in Ukraine on agricultural land. To fulfil this purpose, a study was conducted at the Educational and Research Centre of Mykolaiv National Agrarian University, which included data collection and analysis in different regions of Ukraine, including Dnipro, Mykolaiv, and Zaporizhzhia oblasts. It was found that in Dnipropetrovsk Oblast, soil contamination with lead exceeds the maximum permissible concentration (MPC) by 3 times and fluoride by 1.5 times; in Mykolaiv Oblast, the concentration of lead exceeds the MPC by 5 times, the content of zinc, copper, fluoride, and oil products by a quarter; and in Zaporizhzhia Oblast, the

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concentration of lead exceeds the MPC by 11.17 times, the content of zinc and fluoride is increased by half, petroleum products – by 35%, and phosphates – by 30%. Furthermore, the study confirmed the impact of military operations on the physical and chemical properties of soils, specifically, an increase in the acidity of the soil environment (pH) and the density of the topsoil. To reduce the impact of war on soil and the ecosystem, it is necessary to monitor and assess the effects of military operations, develop and implement environmentally friendly technologies, and restore and rehabilitate the affected areas. The findings of this study can be used to prepare recommendations for the authorities to minimise the environmental impact of military operations on soils

Keywords: agricultural sector; martial law; soil density; heavy metals; petroleum products

INTRODUCTION

Agricultural land is of great significance to society, ensuring food security, economic development, social stability, and environmental sustainability. They create jobs, support rural communities, and help maintain environmental balance. Agriculture is also an essential part of cultural heritage, shaping traditions and customs (Racioppi *et al.*, 2022). Russia's war against Ukraine has caused enormous damage to the country's infrastructure and economy and has put food supplies in Ukraine and beyond at risk. The agricultural sector, which is one of the leading sectors of the economy, has been affected by the hostilities, which may have long-term adverse consequences for the country's further development.

The destruction of agricultural land, infrastructure, and equipment, as well as restrictions on access to these resources, have led to a substantial decline in agricultural production. According to V. Câmpeanu (2022), this decline in production could have grave consequences: food shortages, rising food prices, and a general deterioration in food security. Furthermore, a shortage of agricultural products could affect the country's export capabilities, leading to a decrease in foreign exchange earnings and further economic decline. As a result, this situation could lead to a humanitarian crisis, as access to basic foodstuffs will be limited for many citizens. M.E. Bildirici *et al.* (2022) and V. Biyashev *et al.* (2023) note that the hostilities on the territory of Ukraine, initiated by Russian aggression, have led to serious pollution of agricultural land, which poses a threat to public health, ecology, and the economy. Restoring these lands is critical to ensuring food security.

The study of the impact of hostilities on agricultural land contamination has attracted the attention of many scientists from various fields, including ecology, agronomy, geography, and chemistry. Specifically, A. Drobitko *et al.* (2023) believe that hostilities cause considerable soil contamination with heavy metals and explosives, which have a long-term impact on the environment. Therefore, it is important to systematically monitor pollution and implement bioremediation technologies to clean the affected areas. Pollution of agricultural land has a significant negative impact on soil fertility and agricultural productivity. D. Fiott (2022) believes that pesticides and explosives can alter the chemical composition of soils, reducing their ability to support plant growth. Therefore, developing a strategy aimed at soil restoration, including the use of special agronomic measures and the introduction of resistant plant varieties, is crucial.

J. Bluszcz and M. Valente (2020) note that contamination by explosives and their decay products is a serious threat to agricultural land. These chemical compounds can adversely affect soil microorganisms, which play a key role in maintaining and improving soil fertility. To determine the degree of contamination, detailed laboratory tests are required to accurately assess the level of toxicity. Furthermore, effective methods of chemical detoxification and phytoremediation for the treatment of contaminated land need to be developed. T. Glauben *et al.* (2022) argue that chemical detoxification involves the use of special chemicals to neutralise toxins, while phytoremediation uses plants that can absorb and accumulate harmful substances, thereby cleansing the soil. This approach requires a comprehensive effort that incorporates research, innovative technologies, and coordination between multiple organisations and institutions.

Identifying and monitoring contaminated land is a major step in identifying the sources of pollution and developing effective remediation measures, as well as implementing environmental restoration and protection programmes. M. Griffiths (2021) emphasises the significance of applying a comprehensive approach to the identification and monitoring of contaminated land. T.S. Adebayo and A.O. Acheampong (2021) emphasise that only systematic and detailed research will minimise risks and develop effective strategies aimed at restoring ecological balance and ensuring sustainable agricultural development. This includes the use of the latest technologies to analyse soil conditions, development of methods for cleaning and restoring land, and close cooperation between scientific institutions, government agencies, and agricultural enterprises (Fedoniuk *et al.*, 2024).

Thus, various studies confirm that agricultural land contaminated due to military operations is a multifaceted problem that requires a comprehensive approach. However, despite the considerable amount of research, there are some gaps in the literature, especially regarding integrated methods that combine field surveys, laboratory analysis, and remote technologies to better understand the extent of contamination. The introduction of modern monitoring technologies and the development of effective remediation strategies are critical to ensuring environmental safety and sustainable development of the agricultural sector (Zibtsev *et al.*, 2024). The joint efforts of scientists from different fields can help solve this important problem and secure the future for the affected areas.

The purpose of this study was to assess the extent and nature of the impact of hostilities on agricultural land in Ukraine. To fulfil this purpose, the following tasks were performed: to establish the level of contamination of agricultural land with harmful substances, to determine the impact of military operations on the physical and chemical properties of soils, and to develop strategies for the restoration and management of contaminated and damaged agricultural land.

MATERIALS AND METHODS

The study was based on a set of official sources, specifically, the information base included the Internet resources of the Ministry of Environmental Protection and Natural Resources of Ukraine, the Ministry of Agrarian Policy and Food of Ukraine, and the State Statistics Service of Ukraine, as well as monographic and periodical scientific literature. The theoretical framework of this study included key provisions and findings of scientific research investigating the problems and consequences of the Russian-Ukrainian war, as well as the scientific theories and approaches related to the impact of military operations on ecosystems by anthropogenic pollution, risks and consequences of environmental disasters.

To assess the level of soil contamination caused by military operations, a comprehensive study was conducted at the Training and Research Centre of Mykolaiv National Agrarian University to assess the condition of Ukrainian agricultural land before and after the Russian aggression. To this end, scientific data was collected and analysed in different regions of Ukraine, including Dnipro, Mykolaiv, and Zaporizhzhia Oblasts. Specifically, the data before the invasion were collected in 2020-2021, and during – in 2024. Initially, mapping data and reports from local authorities were collected to help identify areas that could potentially be contaminated. To this end, the areas of the regions with suspected contamination were identified and sites for soil sampling were established.

Number and location of plots for each region:

1. Dnipropetrovsk Oblast:

Contaminated areas:

- Site 1 – Ivanivka village (Dnipro region), where the hostilities took place;
- Site 2 – the city of Pavlohrad, where the shelling took place;
- Site 3 – Marianka village (Synelnykove region), which was affected by the explosions.

Clean areas:

- Site 1 – Orlivshchyna village (Novomoskovsk region), where no hostilities took place;
- Site 2 – Tomakivka village (Tomakivka region), where the natural soil condition has been preserved.

2. Mykolaiv Oblast:

Contaminated areas:

- Site 1 – Mykolaiv city, central district, where the shelling was recorded;
- Site 2 – Shyroke village (Snihurivka region), which was affected by hostilities;
- Site 3 – Blahodatne village (Bashtanka region), which was bombed.

Clean areas:

- Site 1 – Kovalivka village (Mykolaiv region), where no hostilities took place;
- Site 2 – Parutyne village (Mykolaiv region), where the natural conditions are still stable.

3. Zaporizhzhia Oblast:

Contaminated areas:

- Site 1 – Zaporizhzhia city, Khortytskyi region, where the shelling took place;
- Site 2 – Orikhiv city, which has sustained serious damage;
- Site 3 – Mala Tokmachka village (Polohy region), where intense fighting took place.

Clean areas:

- Site 1 – Komyshuvakha village (Zaporizhzhia region), where no military operations were recorded;
- Site 2 – Novoiakovlivka village (Zaporizhzhia region), where the natural soil condition has been preserved.

Thus, for each region, three contaminated sites and two clean sites were selected for research. This allows comparing the condition of the soil before and after the hostilities and assess the level of soil contamination. The soil contamination study methodology included: sampling in the areas after the Russian invasion from the following depths: 0-10 cm, 10-20 cm, and 20-30 cm to obtain a representative and average sample; preparation of soil samples for analysis (drying and grinding to the required fraction); determination of the content of pollutants in soil samples (lead, fluorine, cadmium, mercury, sulphur, nickel, copper, cobalt, zinc, and oil products), soil pH and soil density; analysis of the data obtained. For each of the identified elements, a pollution index (P) was calculated based on the ratio of the element's concentration in the soil to its maximum permissible concentration (MPC), as well as a total pollution index for these elements – as the sum of the indices.

At the beginning of the study, a thorough check of the area for explosive devices was mandatory. A soil drill was used to collect soil samples, while the collected soil samples were examined in the laboratories of Mykolaiv National Agrarian University. Specifically, the content of heavy metals was determined by gas chromatography with a GC-MS mass spectrometry detector (Shimadzu, Japan); the concentration of nitrates, phosphates, and petroleum products – by gas chromatography; the reaction of the soil environment (pH) – using a PCE-PH 18 PCE pH meter (Instruments, Germany); the density of the topsoil – according to the method of M.A. Kachinsky.

All collected data was subjected to statistical analysis. To process the research results for statistical significance, the multivariate method of analysis of variance MANOVA was used, using Microsoft Excel software and the Statistica 10 software package. The differences between the results were assessed using the Student's t-test at a significance level $P \leqslant 0.05$.

RESULTS

The military actions launched by Russia have led to considerable environmental disasters in Ukraine, particularly in its nature reserves. As a result of these actions, large areas of forests were destroyed, and unique ecosystems were seriously damaged. Over 200,000 hectares of territory are contaminated with shells, mines, and ammunition fragments, which poses massive risks to natural biodiversity and public health. Explosions of rockets, artillery shells, bombs, drones, and multiple launch rocket systems cause the destruction of the top fertile soil layer. This layer, which has been formed over centuries, is key to agriculture and ecosystem conservation. The explosions also release toxic compounds into the soil, including carbon dioxide, nitrous oxide, water vapour, formaldehyde, cyanide vapour, and other toxicants. These substances not only reduce soil quality, but can also migrate into water systems, threatening human and animal health.

The war considerably deteriorates the physical and chemical properties of the soil, and as a result, its fertility decreases. Specifically, changes in soil structure can lead to a loss of water and nutrient retention capacity, which are critical for plants. Explosions can also cause mechanical damage to the soil, making it difficult to use for agriculture. Ukrainian soils have already lost about 30% of their humus over the past century due to intensive agriculture and other anthropogenic factors. Military actions only accelerate this process (Panfilova, 2021). Humus is a vital component of soil that ensures its fertility and stability. The loss of humus leads to a decrease in the productivity of agricultural land, which can have serious economic consequences.

Ukraine's nature reserves, which are home to a variety of flora and fauna, are also affected by the hostilities. Pollution, habitat destruction, and the direct destruction of plants and animals lead to a considerable decline in biodiversity (Shevchuk, 2024). Restoring these ecosystems could take decades and require significant efforts and resources. According to the Ministry of Environmental Protection and Natural Resources of Ukraine, the condition of Ukrainian land has deteriorated substantially since the full-scale invasion. Soil contamination increased by an average of 30-60% compared to the full-scale invasion (Fig. 1).

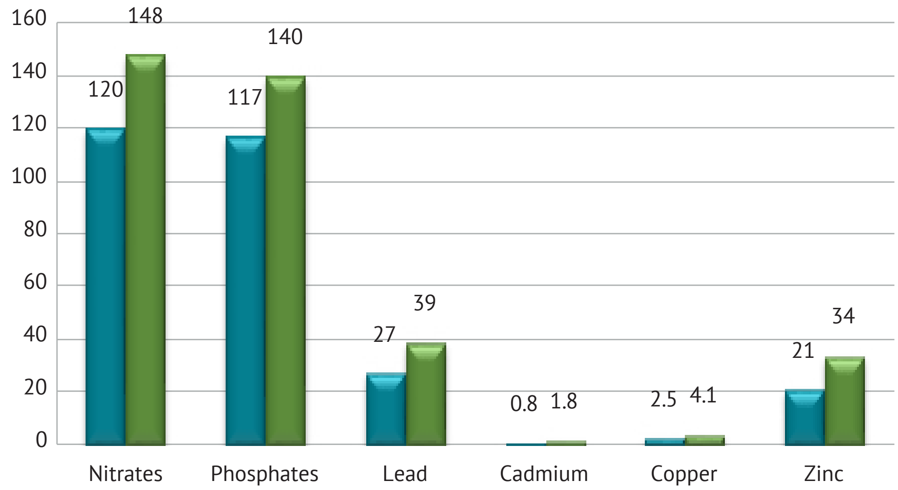

***Figure 1**. Changes in pollution of Ukrainian land before and after the full-scale invasion of Russia, mg/kg*
***Source:** compiled by the authors of this study*

Thus, the state of soil contamination in Ukraine before the war was relatively safe, as the content of harmful substances met safety standards and did not exceed the MPC. However, after prolonged hostilities, there has been a significant increase in the content of heavy metals, nitrates, phosphates, and petroleum products, which exceeds the standard levels. The findings of the study of Ukrainian agricultural land after the Russian aggression in Dnipro, Mykolaiv, and Zaporizhzhia oblasts confirmed that the level of soil contamination is high, especially in areas where active military operations were ongoing, and the concentration of pollutants in the soil exceeds the permissible limits (Table 1).

Harmful substance	Pollutant content			MPC
	Dnipropetrovsk Oblast	Mykolaiv Oblast	Zaporizhzhia Oblast	
Mercury	2	2.2	2.4	2.1
Copper	3.4	3.8	4.1	3
Zinc	22.5	30	35.4	23
Lead	18.4	29.5	67	6
Sulphur	178	182	192	160
Fluoride	3.4	3.5	4.2	2.8
Cadmium	1.6	1.7	2	1.5
Nickel	4	4.3	4.6	4
Cobalt	4.5	5.2	5.7	5
Petroleum products	968	1,240	1,350	1,000
Phosphates	105	125	157	120
Nitrates	127	126	154	130

Table 1*. Level of soil contamination after the invasion of Russia, mg/kg of soil*

Source: *compiled by the authors of this study*

Specifically, in the Dnipropetrovsk Oblast, soils are contaminated with various harmful substances, including lead and fluoride, which significantly exceed the MPC, with lead exceeding the MPC by three times and fluoride – by one and a half times. Copper, sulphur, and cadmium also exceed the permissible levels, although to a lesser extent. Other pollutants, such as mercury, zinc, nickel, cobalt, petroleum products, phosphates, and nitrates, are within or close to the permissible limits. Analysis of soil contamination in Mykolaiv Oblast also shows a fivefold exceedance of the MPC for lead – 29.5 mg/kg, zinc content – 30% above the MPC, copper and fluoride – 25% above the MPC, and petroleum products – 24% above the MPC. Other harmful substances, such as mercury, copper, sulphur, cadmium, nickel, cobalt, phosphates, and nitrates, also exceed permissible levels, requiring immediate measures to clean and control soil contamination. In Zaporizhzhia Oblast, the concentration of lead was found to be 11.17 times higher than the MPC, while zinc content was increased by 54%, fluorine – by 50%, petroleum products – by 35%, and phosphates – by 30%. The Zaporizhzhia Oblast has considerable soil contamination with harmful substances, which indicates serious environmental problems and harmful effects on people. Such soil contamination can also lead to disruption of ecosystems, changes in land fertility, and the quality of crops grown. Therefore, urgent measures are needed to clean the soil and prevent further contamination. In the three regions of Ukraine under study (Dnipropetrovsk, Mykolaiv, and Zaporizhzhia oblasts), there is a critical level of soil pollution, with total indices of 14.55, 18.43, and 25.56, respectively. The largest exceedances of the MPC were recorded for lead, petroleum products, copper, and zinc, especially in Zaporizhzhia Oblast (Table 2).

Table 2*. Indices of soil contamination with harmful substances*

Harmful substance	Soil pollution index		
	Dnipropetrovsk Oblast	Mykolaiv Oblast	Zaporizhzhia Oblast
Mercury	0.95	1.05	1.14
Copper	1.13	1.27	1.37
Zinc	0.98	1.3	1.54
Lead	3.07	4.92	11.17
Sulphur	1.11	1.14	1.2
Fluoride	1.21	1.25	1.5
Cadmium	1.07	1.13	1.33
Nickel	1	1.08	1.15
Cobalt	0.9	1.04	1.14
Petroleum products	0.97	1.24	1.35
Phosphates	0.88	1.04	1.31
Nitrates	0.98	0.97	1.18
Total pollution index	14.55	18.43	25.56

Source: *compiled by the authors of this study*

Notably, the war also affected the acidity (pH) of soils through several mechanisms. The use of explosives leads to the release of nitrates and sulphates, which acidify the soil. The destruction of residential buildings and warehouses promotes the spread of building materials such as concrete and cement, which release alkalis that also change the pH of the soil. Leaks of oil products from military equipment cause soil acidification, while the use of chemicals, including defoliants and agrochemicals, changes the composition of the soil and affects its acidity (pH). The degradation of vegetation as a result of military operations reduces the amount of organic matter in the soil and weakens its buffering properties, making the soil more vulnerable to changes in pH. Military operations also lead to groundwater contamination, which increases the content of acids or alkalis in the soil (Lopushnyak *et al.*, 2022). Together, these factors cause significant changes in soil pH, which can have dire consequences for local ecosystems and agricultural land, reducing soil fertility and making it difficult to grow crops that require a neutral or near-neutral pH to grow optimally. The study found that military actions on the part of Russia affected the change in the pH of the environment in the soils of the oblasts under study (Table 3).

***Table 3**. Indicators of soil reaction*

Oblast	Soil layer		
	0-10 cm	10-20 cm	20-30 cm
Dnipropetrovsk Oblast	5.8	5.9	6.3
Mykolaiv	6	6.2	6.5
Zaporizhzhia	5	5.5	6.3

***Source:** compiled by the authors of this study*

According to the data obtained, in Zaporizhzhia Oblast, the pH of the soil environment is the most acidic among the three oblasts, especially in the tilth (0-10 cm) soil layer. In the Mykolaiv region, the soil pH is more neutral, which may contribute to better conditions for plant growth. In the Dnipropetrovsk Oblast, pH values range from slightly acidic to almost neutral in the deeper soil layers. Changes in pH can affect the availability of nutrients to plants and the overall health of the ecosystem. The military and anthropogenic load causes a mechanical impact on the soil, which lies in deformation of the soil cover. The high weight of tracked and wheeled vehicles used by the military leads to soil compaction, which has negative consequences, such as disruption of the water balance of soils, erosion, soil over-compaction, and the transition of water-saturated dispersed soils to a fluid state due to the destruction of structural bonds under dynamic load (Shaforost *et al.*, 2024). Furthermore, the mechanical impact is accompanied by chemical contamination of the soil, which leads to the permanent decommissioning of the land and a ban on its use. These consequences could have a serious impact on agricultural development and the environment in the future. The findings suggest that soil density varies by region and depth. In Dnipropetrovsk Oblast, the density of the topsoil (0-30 cm) is 1.22 g/cm^3, in Mykolaiv Oblast – 1.25 g/cm^3, and in Zaporizhzhia Oblast – 1.19 g/cm^3 (Table 4).

***Table 4**. Soil density, g/cm^3*

Oblast	Soil layer			
	0-10 cm	10-20 cm	20-30 cm	0-30 cm
Dnipropetrovsk	1.15	1.21	1.3	1.22
Mykolaiv	1.19	1.24	1.32	1.25
Zaporizhzhia	1.12	1.2	1.26	1.19

***Source:** compiled by the authors of this study*

Thus, pollution and changes in the physical and chemical properties of Ukrainian land are a genuine issue, especially after the invasion of Russia. Many of these contaminants have become even more dangerous as they are caused by the use of military equipment and weapons. The study found that military operations have a significant impact on soil conditions, particularly in the east of Ukraine. The negative effects of this impact include soil contamination due to hostilities and illegal dumping of chemicals, which poses a serious threat to both the health of the local population and the environment.

The findings indicate the need for immediate measures to minimise the impact of the hostilities on the soil and ecosystem. This includes the development and implementation of environmentally friendly technologies for military operations, enhanced monitoring and assessment of the impact of military operations on soil and the ecosystem, and measures to restore and reclaim the affected areas. It is also important to educate military personnel on environmental safety and implement programmes to restore and protect soil and the ecosystem, including cooperation with international organisations and experts to share practices and receive support in minimising the negative impact of military operations on the environment.

To reduce the risk of soil contamination, it is also necessary to establish strict controls over the use of pesticides and chemicals in agriculture and industry. Regular monitoring of soil contamination, especially in areas affected by military operations, will help to identify hazards promptly and take the measures necessary to prevent further spread of contamination. For soil restoration, it is recommended to use special technologies and materials that will help restore soil fertility and biological composition, such as biological fertilisers and cultivation of special plant species. The Ukrainian authorities should take decisive steps to reduce the risk of soil contamination, including monitoring its quality and cleaning the soil if necessary. Furthermore, it is crucial to restore peaceful control over the territories occupied by Russian militants to ensure the safety of the local population and to carry out monitoring and soil clean-up activities.

DISCUSSION

The war started by Russia has led to a significant increase in soil pollution in Ukraine, which poses a threat not only to human health but also to global food security. According to various scientific studies, the military conflict has led to the contamination of a large area of land equivalent to the size of an average European country (De Groot *et al.*, 2022). Ukraine has already struggled with soil pollution due to decades of industrial activity and poor waste management practices. The ongoing war has only exacerbated the problem, leading to the destruction of infrastructure and waste management systems, and increasing the risk of soil, water, and air pollution (Babenko *et al.*, 2021).

The study confirmed that toxic elements such as lead, cadmium, arsenic, and mercury from ammunition and weapons leach into the soil, contaminating the food chain, and posing a risk to agricultural production. Furthermore, M. Cláudia *et al.* (2022) show that soil, water, and air pollution has long-term consequences for the ecosystem, and therefore it is urgent to address this problem. The findings also suggest an increase in toxic substances in the soil, which will lead to degradation of its physical and chemical properties and disruption of the biological balance, affecting various aspects of the agro-ecosystem, including soil fertility and crop quality. According to O. Belcher *et al.* (2019), microorganisms that ensure soil fertility become vulnerable to toxins, which will reduce humus formation and adversely affect soil structure.

The conducted study confirms the statement of M. Jankowski and M. Gujski (2022), who note that as the war intensifies, pollutants from munitions explosions can seriously damage the soil and the environment, which affects crop growth, quality, and quantity of crops. The researchers also note that soil contamination with toxicants disrupts the ecological balance and has a harmful effect on soil biota, which is essential for maintaining soil fertility. The results highlight the significance of controlling the level of toxic contamination of soil and water sources to ensure food safety. As a confirmation, V. Gamajunova *et al.* (2021) also emphasise that toxic substances can actively accumulate in plants, which affects food safety and has a potentia lly negative impact on human health. This poses a threat, as consumption of such products can cause negative consequences for the body, depending on the type of toxic substances.

A. Drobitko and A. Alakbarov (2023) showed that in the areas where military operations took place, the concentration of metals in the soil considerably exceeded the permissible standards and posed a significant threat to environmental stability. This contamination will have far-reaching consequences for the local population, who may suffer negative health impacts through contact with contaminated soil and water sources. Furthermore, environmental degradation can exacerbate socio-economic problems, making post-war recovery more difficult. Comprehensive environmental programmes aimed at cleaning the soil and restoring the ecosystem, as well as the introduction of strict legal regulations to prevent similar situations in the future, may help to address the existing threats. In support of this, K.K. Khaletska and N.O. Sydorenko (2019) find that the war in Ukraine will lead to a large drop in agricultural yields. The Russian invasion has resulted in over 20% of Ukraine's arable land being occupied, Russia systematically attacking agricultural infrastructure and farmers' facilities, and soil contaminated with toxic substances that could take decades or even hundreds of years to remediate.

Thus, the problem of soil contamination in Ukraine is truly complex and requires a comprehensive approach to solving. Limited resources, political instability, and the ongoing war pose considerable obstacles to the effective implementation of environmental protection measures. However, the findings and opinions of researchers such as A. Panfilova and V. Fedorchuk (2022) point to initiatives aimed at reducing soil pollution and improving environmental sustainability. One of these initiatives is the development of waste management systems aimed at efficient use and recycling of waste to reduce its impact on the environment. An additional initiative, according to H. Van Meijl *et al.* (2022), is to promote sustainable agricultural practices that involve the use of less fertiliser and plant protection products, as well as more frequent use of organic tillage methods. These approaches help to preserve soil fertility and prevent soil contamination with toxic substances.

V. Astrov *et al*. (2022) also believe that a monitoring system should be developed that could become a key tool for the prevention and detection of pollution in real time. It would ensure constant monitoring of the environment, allowing for a prompt response to any new sources of pollution and minimising their impact on natural resources and human health. This approach would improve the effectiveness of soil and water quality control, ensuring safety for all life processes. Furthermore, V. Lopushnyak *et al*. (2022) also concur that restoring ecosystems and soil fertility is a critical task for Ukraine. This will require a comprehensive approach, including clean-up of contaminated areas, reforestation, implementation of sustainable agricultural practices, and soil monitoring. International cooperation and support can play a significant role in this process by providing the necessary resources and technology for recovery. A. Panfilova (2021) notes that it is crucial to use reliable environmental monitoring methods to accurately assess the environmental impact of military operations. These include remote sensing, mathematical and simulation models, mobile laboratories, and unmanned aerial vehicles as particularly effective means. The use of these technologies makes it possible to collect objective data on the state of the environment during and after military conflicts, which is critical for making informed decisions on the conservation and restoration of ecosystems (Kravchuk *et al*., 2023).

Thus, Russia's invasion of Ukraine was a turning point for the entire world with significant geopolitical consequences. The war is changing the global landscape, disrupting the world order, and threatening security and stability around the world. In a globalised world, the effects of war in one region are felt far beyond its borders through complex supply chains and economic ties. Soil contamination in Ukraine caused by the hostilities is affecting the agricultural sector and has a potentially negative impact on global food safety. Considering the urgency and seriousness of the soil pollution problem in Ukraine, it is vital to emphasise the need for joint efforts by the government, international organisations and civil society. Implementing effective measures to reduce the environmental impact of industrial and military activities is an urgent task. Sustainable management strategies, improved waste management, and innovative approaches to environmental monitoring will be key to achieving environmental safety and sustainability goals. Only through cooperation and global support can successful solutions be provided to minimise the negative impact on the environment and ensure a sustainable improvement in the quality of life of the population.

CONCLUSIONS

The military conflict started by Russia in Ukraine has created a serious threat of soil contamination, destruction of ecosystems, forests, and natural biodiversity. The findings of this study of the state of Ukrainian agricultural land after the Russian aggression reflect serious soil pollution problems in the Dnipropetrovsk, Mykolaiv, and Zaporizhzhia oblasts.

The study found that in the Dnipropetrovsk Oblast, soils are contaminated with various harmful substances, including lead and fluoride, which exceed the MPC by 3 and 1.5 times, respectively. In Mykolaiv Oblast, the concentration of lead exceeds the MPC by 5 times, zinc is 30% higher than the MPC, copper and fluoride exceed the limit by 25%, and petroleum products – by 24%. In Zaporizhzhia Oblast, the concentration of lead exceeds the MPC by 11.17 times, the content of zinc has increased by 54%, fluorine by 50%, petroleum products – by 35%, and phosphates – by 30%. The total indices of soil pollution in the three regions of Ukraine under study are 14.55, 18.43, and 25.56, respectively. Furthermore, military actions have affected the pH of the soil environment towards increased acidity, while the military and anthropogenic load has caused mechanical impact on the soil, which has led to soil compaction. The density of the topsoil (0-30 cm) varies by region and depth and is 1.22 g/cm^3 in Dnipropetrovsk Oblast, 1.25 g/cm^3 in Mykolaiv Oblast, and 1.19 g/cm^3 in Zaporizhzhia Oblast.

To reduce the impact of the hostilities on the soil and ecosystem, a range of measures must be taken at once. This includes the development and implementation of environmentally friendly technologies, systematic monitoring and assessment of the impact of military operations on soil and ecosystems, and restoration and reclamation of damaged areas. It is also important to strengthen legal control over the use of fertilisers, plant protection products, and other chemicals in agriculture and industry, and to regularly monitor soil pollution, especially in the areas most affected by Russia's invasion. Soil restoration also requires the use of special technologies and materials that will restore soil fertility and biological composition. The authorities should take various measures, including monitoring the quality of the soil and cleaning it if necessary, as well as restoring civilian control of the territories occupied by Russian troops.

Prospects for further investigation include exploring the possibilities of using reclaimed soils for ecosystem and biodiversity regeneration. Limitations of this study lie in the difficulty of accessing some areas affected by military conflicts in terms of data collection and due monitoring.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Ідентифікація та моніторинг забруднених сільськогосподарських земель внаслідок бойових дій

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Анотація. Напад росії на Україну спричинив широкомасштабне забруднення сільськогосподарських земель, що наразі є нагальною екологічною проблемою, важливою для здоров'я людей та сталого розвитку країни. У зв'язку з цим, мета дослідження полягала в аналізі наслідків військових дій в Україні на сільськогосподарські землі. Для досягнення мети було проведено дослідження на базі Навчально-науково-практичного центру Миколаївського національного аграрного університету, яке включало збір та аналіз даних у різних регіонах України, зокрема у Дніпропетровській, Миколаївській та Запорізькій областях. Встановлено, що у Дніпропетровській області забруднення ґрунтів свинцем перевищує гранично допустимі концентрації (ГДК) у 3 рази, а фтором – у 1,5, у Миколаївській області концентрація свинцю перевищує ГДК в 5 разів, вміст цинку, міді, фтору та нафтопродуктів – на чверть, а у Запорізькій області концентрація свинцю перевищує ГДК в 11,17 разів, вміст цинку, фтору збільшено на половину, нафтопродуктів – на 35 %, а фосфатів – на 30 %. Крім того, у дослідженні підтверджено, що існує вплив військових дій на фізико-хімічні властивості ґрунтів, зокрема, відмічено збільшення кислотності реакції ґрунтового середовища (pH) та щільності орного шару ґрунту. Для зменшення впливу війни на ґрунти та екосистему, слід здійснювати моніторинг та оцінку наслідків військових дій, розробляти та впроваджувати екологічно безпечні технології, а також проводити відновлення та рекультивацію постраждалих територій. Результати дослідження можуть бути використані для підготовки рекомендацій органами влади щодо мінімізації екологічного впливу військових дій на ґрунти

Ключові слова: аграрний сектор; військовий стан; щільність ґрунту; важкі метали; нафтопродукти