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Ecological and economic approaches to assessing damage caused to agricultural land by military actions

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Abstract. This article aimed to evaluate the ecological and economic consequences of military actions on agricultural land in Ukraine, identifying key indicators to assess the environmental impact of warfare and facilitate subsequent agribusiness restoration in the post-war period. The research was based on a comprehensive analysis of the environmental, economic, and social consequences of military actions for Ukraine's agricultural sector. This analysis used field surveys, satellite data, laboratory soil analyses, and official statistics. The research established that more than 200,000 hectares of agricultural land were damaged as a result of hostilities, around 20% of which was the most fertile land taken out of agricultural use. Exceedances of permissible levels of heavy metals in soil were recorded in the Kharkiv, Donetsk, Mykolaiv, Luhansk and Zaporizhzhia regions: lead by three times, cadmium by 2.5 times, arsenic by twice, nickel by more than twice and zinc by 1.6 times. Conversely, no exceedance of the maximum permissible concentrations of mobile forms of heavy metals, including lead and cadmium, was detected within the agricultural lands studied in the Vyshhorod district of the Kyiv region. Significant exceedances of background levels of heavy metals in soil pose long-term risks to the quality and safety of food products, lead to economic losses, and endanger public health. This emphasises the importance of monitoring soil contamination in areas affected by hostilities and at agricultural enterprises. The research revealed that direct economic losses included the loss of over 4 million hectares of crops and the destruction of over 100 grain storage facilities with a total capacity of 2 million tonnes. There was also a decrease in yields on over 500,000 hectares due to the loss of irrigation systems. Indirect losses were reflected in a 15-20% reduction in production, a 35-40% increase in food prices, a 40% decline in investment volumes, and the suspension of operations for more than 30% of small and medium-sized enterprises. The socio-economic consequences included the migration of over 6.5 million people and a deterioration in food security. However, the territory in question also possesses significant potential for recovery

Keywords: soil degradation; agricultural sector; costs; food security; state support

INTRODUCTION

The relevance of the research topic was determined by significant transformations in Ukraine's agricultural sector resulting from military action. Damage to the soil cover, destruction of infrastructure, loss of harvests and technical resources created multidimensional consequences requiring systematic scientific assessment. Combining ecological and economic approaches in the assessment of damage was deemed necessary because land degradation and loss of productivity were reflected not only in a reduction in agricultural production potential, but also in a decline in investment attractiveness and an increase in socio-economic risks. Scientific research into the impact of military action on the economy and the environment provides a comprehensive understanding of the negative consequences of armed conflict for various sectors, including agriculture. L. Khomych & N. Khrushch (2024) have proposed an analytical assessment of the impact of the war on Ukraine's economic activity. This contributes to understanding of the extent of the structural

changes to the national economy caused by the conflict. The impact on the agricultural sector is particularly significant, as war leads to reduced production, lost land and increased investment risks. A. Verstyak (2023) described methods for assessing environmental damage, helping to analyse the impact of war on agricultural land. Soil contamination with heavy metals and ecosystem degradation lead to substantial economic losses. Meanwhile, O. Sushchenko & V. Tymkovan (2024) examined the impact of martial law on the development of agro-industrial formations, confirming the importance of studying the socio-economic consequences of war for the agricultural sector, as well as the need to develop effective recovery models. The environmental consequences of war are also addressed in L.A. Sakhno's (2023) research, which highlights the impact of military operations on accounting policies and land resource auditing. This is directly relevant to the need to combine ecological and economic approaches to restoring agricultural land after war.

A. Kucher (2022), meanwhile, proposed changes to the methods used to determine the extent of damage resulting from mechanical, physical, chemical, physico-chemical and biological forms of soil degradation, based on a cost-based methodological approach. T.M. Gerlyand *et al.* (2024) presented examples of integrating educational practices into the reconstruction of the agricultural sector, emphasising the importance of environmental education for the sustainable development of rural areas. When assessing the environmental consequences of hostilities on soils, particularly agricultural land, results from studies analysing changes in the physicochemical and toxicological characteristics of soils are particularly relevant. O.V. Dmytrenko *et al.*'s (2023) study focuses on the ecotoxicological assessment of sod-podzolic soil under the influence of military actions. The authors identified changes in the soil's agrochemical indicators, demonstrating the need to develop methods for assessing and restoring soils after hostilities. Another important aspect is monitoring the environmental consequences, particularly the impact of fires resulting from hostilities. A.E. Honcharova (2024) examines the environmental consequences of military actions in Ukraine, including the impact of fires on ecosystems. The author emphasises the necessity of a comprehensive approach to monitoring and assessing environmental consequences, including studying the impact of fires on soils and agricultural land. These studies emphasise the importance of taking an integrated approach to assessing and restoring agricultural land after conflict, particularly by applying a cost-based method to determine the extent of the damage based on the cost of soil restoration. R. Wenning & T.D. Tomasi (2023), for example, applied natural resource damage assessment approaches to identify the scale of environmental damage by evaluating ecosystem services. Satellite-based assessment of agricultural crop losses in near-real time is also widely used. K. Deininger (2023) conducted such an assessment, making it possible to record the spatial reduction of agricultural areas and demonstrating the effectiveness of remote sensing for rapidly monitoring damage. M. Nehrey & R. Finger (2024) examined the impact of the initial phase of the full-scale war in

Ukraine on soil degradation and the decline in land productivity. Their work analysed regional differences in degradation rates and the development of differentiated recovery strategies.

A synthesis of scientific sources showed that modern approaches to studying the ecological and economic consequences of military action involve analysing soil conditions, biodiversity and ecosystem losses, and the economic impact of losses resulting from hostilities. These approaches also include the application of satellite technologies and the development of institutional mechanisms for restoring degraded territories, including agricultural land. Meanwhile, some studies have focused on specific aspects of the impact of military action on the environment and agricultural production. However, insufficient attention has been paid to studying ecological-economic approaches or developing an integrated model for assessing damage to the agricultural sector caused by military actions. This article aimed to investigate the scale of damage to agricultural land resulting from military actions, as well as changes to its ecological and economic characteristics. The article also aimed to determine priority areas for restoring productivity and safety within Ukraine's agricultural sector. To achieve this, the following tasks were set: to determine the scale of soil degradation and the level of contamination of agricultural land resulting from active hostilities, comparing regions; to assess direct and indirect economic losses in the agricultural sector resulting from hostilities, including losses of crops, infrastructure, and investment attractiveness; to analyse the socio-economic consequences of the war and prospects for the management of agricultural enterprises in the post-war period were outlined.

MATERIALS AND METHODS

Conducted between 2022 and 2025, the research aimed to provide a comprehensive examination of the ecological and economic consequences of military actions for Ukraine's agricultural sector. The analysis was based on agricultural lands in the central, eastern and southern regions, which were the most significantly impacted by hostilities. Territories were selected based on official data from the Ministry of Agrarian Policy

presented... (2024), the State Statistics Service of Ukraine (2024) and a Copernicus-enabled assessment (2023). Satellite images presented in *Farming Amidst a War* (2023) enabled the scale of damage to arable land and infrastructure degradation in the Kyiv region to be identified. Inclusion in the sample was dependent on the availability of confirmed data regarding damage to soil cover, infrastructure destruction, or productivity decline resulting from military actions. Territories where information was incomplete or not confirmed by independent sources

were excluded from the research. To assess the environmental consequences, studies of pollutant concentrations in soil were conducted in agricultural land located in the de-occupied territories. Analytical methods were employed to gather data on the contamination of agricultural land in the liberated areas of the Donetsk, Luhansk, Kharkiv, Zaporizhzhia, and Mykolaiv regions. Field studies were carried out within agricultural lands in the Kyiv region that had been liberated and experienced the impact of hostilities in 2022 (Fig. 1).

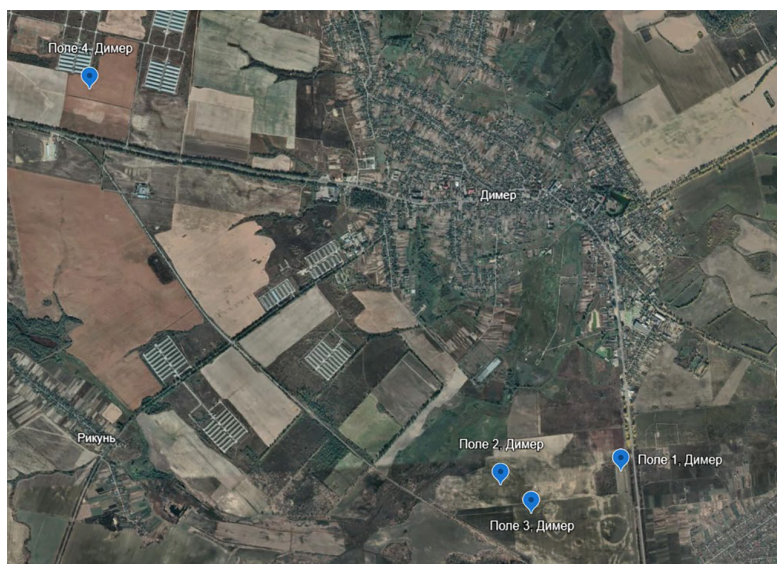


Figure 1. Location of the studied sites within the Vyshhorod district of the Kyiv region on agricultural land affected by hostilities in 2022

Source: Google Maps (n.d.)

The satellite image shows the location of the agricultural plots that were studied within the territory of the Dimer settlement (Vyshhorod district). The individual fields selected for assessing soil conditions and the consequences of military impact are indicated. Sampling to determine agrophysical and agrochemical soil indicators, as well as pollutant content, was carried out in accordance with ISO 10381-1:2004 (2006), ISO 10381-2:2004 (2006) and ISO 10381-4:2005 (2007). Composite soil samples were taken from the 0-30 cm layer using a manual sampler. To ensure comparability, control soil samples were also taken from areas

unaffected by military action. Heavy metal concentration studies (cadmium (Cd), cobalt (Co), nickel (Ni), lead (Pb) and chromium (Cr)) were conducted using a combination of chromatographic and mass spectrometry techniques with Agilent 1260, 1290 and 7890B liquid and gas chromatographs (Agilent 6125, 6460 and 5977 and 7000 detectors). The biodiversity of the Kyiv, Kharkiv and Zaporizhzhia regions was assessed using indicators of soil microbiological activity and the abundance of saprophytic organisms obtained from control plots. To this end, the Shannon (H') and Simpson (D) indices, as well as the abundance of saprophytic organisms in the

studied plots, were employed in accordance with widely accepted methodologies.

The economic component of the research was based on official statistics from the World Bank (2023), the OECD (2023), and the FAO of Ukraine. Food Security (2024). Direct losses were assessed by considering the area of lost crops, the volume of damaged or destroyed warehouses and grain storage facilities, the number of lost agricultural machines, and the area of land left without irrigation. Indirect losses were calculated based on reduced enterprise productivity, declining exports and falling investment activity. To evaluate the financial risks to agribusinesses, lending dynamics and changes in interest rates were analysed using data from the National Bank of Ukraine (2025). The socio-economic component of the study was based on statistical materials from the Country Report: Ukraine (2022) and Food Security and Livelihoods (2023). The analysis examined increases in food prices, household budget composition, the scale of internal and external migration, and the reduction in labour potential within the agricultural sector. Statistical analysis was carried out using SPSS Statistics 26 software.

RESULTS AND DISCUSSION

Environmental consequences of military actions for agricultural land

In the context of Ukraine's current environmental policy, the key areas of environmental protection and ecological safety defined in Law No. 188/98-BP (1998) provide for the implementation of sustainable development principles, the rational use of natural resources and consideration of environmental risks, which intensify under conditions of armed conflict. In view of the significant losses incurred by the agricultural sector, particularly in terms of soil degradation and territorial contamination resulting from hostilities, these priorities assume particular relevance in the context of post-war agricultural recovery and ensuring the country's environmental stability. In this context, it is important to assess the current state of agricultural land in areas affected by military action. During the active phase of hostilities, significant soil degradation was recorded, characterised by mechanical soil disturbance, changes in

physicochemical properties, and pollutant accumulation. The mechanical pressure exerted by heavy military equipment caused the upper soil layers to become compacted, which negatively affected their agrophysical properties (porosity, water permeability, aeration, etc.), agrochemical indicators, and pollutant content. This has led to a reduction in agricultural land productivity, accelerated degradation processes and, in some cases, made it impossible to produce high-quality, safe agricultural products. The destruction of hydraulic structures, particularly the Kakhovka Hydroelectric Power Plant, resulted in heavy metals such as arsenic, nickel, and zinc migrating from bottom sediments into the Dnipro River and Black Sea ecosystems (Solokha *et al.*, 2024). The use of contaminated water to irrigate adjacent agricultural land resulted in soil contamination, creating long-term environmental risks. The biodiversity of agroecosystems declined, as evidenced by a reduction in the number of saprophytic microorganisms and invertebrates that play a fundamental role in forming soil structure.

According to estimates by Ukraine's State Statistics Service (2024), more than 200,000 hectares of agricultural land were contaminated and damaged during the active phase of hostilities. Around 20% of the most valuable agricultural land was taken out of use as it was impossible to carry out agrochemical investigations, even after de-occupation. The chemical contamination of soils with heavy metals such as lead and cadmium, which significantly exceeded standard values, has intensified degradation processes and reduced the productivity of agricultural enterprises. According to the Ministry of Agrarian Policy presented... (2024), grain harvest losses in 2023 amounted to over 4 million tonnes, equivalent to a 25% reduction in gross output, with farmers incurring losses in excess of USD 1.5 billion. According to data from the State Statistics Service of Ukraine (2024), over 20% of agricultural land has been taken out of use due to soil degradation, limiting the potential to restore agricultural production and export capacity. This leads to lower farm incomes and an annual reduction in GDP of 0.8-1.0%. To establish the actual impact of hostilities on agricultural enterprise territories and determine

ecological and economic approaches to assessing the impact of military actions, a series of analytical, field, and laboratory studies were carried out. A study of heavy metal content in the arable soil layer was conducted on the basis of statistical data in territories where active hostilities took place, particularly involving the use

of munitions and the movement of heavy equipment, in the Kharkiv, Donetsk and Luhansk regions. Exceedances of the maximum permissible concentrations (MPCs) of the heavy metals lead, cadmium, chromium and arsenic were identified in the soils of the Kharkiv, Luhansk and Zaporizhzhia regions (Table 1).

Table 1. Specific indicators of the environmental consequences of military actions for agricultural land

Indicator	Value	Unit of measurement	Standard / Reference value
Area of damaged land	200,000	ha	–
Share of the most fertile land taken out of use	20	%	–
Soil lead (Pb) concentration	95	mg/kg	≤ 32 mg/kg (standard)
Soil cadmium (Cd) concentration	2.5	mg/kg	≤ 1.0 mg/kg (standard)
Soil arsenic (As) concentration	20	mg/kg	≤ 10 mg/kg (standard)
Soil zinc (Zn) concentration	350	mg/kg	≤ 220 mg/kg (standard)
Soil nickel (Ni) concentration	85	mg/kg	≤ 40 mg/kg (standard)

Source: compiled by the authors on the basis of data from The Ministry of Agrarian Policy presented... (2024)

A substantial exceedance of standard values was recorded: lead by three times, cadmium by 2.5 times, arsenic by twice, nickel by more than twice, and zinc by 1.6 times. The obtained data indicate a probable reduction in the area of agricultural land suitable for producing safe, high-quality products, as well as the need to restrict the use of such land and to develop protocols for applying new reclamation methods and

approaches to cultivating crops on contaminated soils. The rising risks to public safety, loss of fertile land and need for long-term land reclamation measures create long-term economic risks. Field studies carried out in the Kyiv region showed elevated levels of cadmium, cobalt, nickel, lead, and chromium compared to background values, though without exceeding maximum permissible concentrations (MPCs) (Table 2).

Table 2. Content of mobile forms of heavy metals in fields liberated from military actions on agricultural land in the Vyshhorod district of Kyiv region

Indicator	Value	Unit of measurement	MPC for mobile forms
Soil lead (Pb) concentration	0.85 ± 0.1	mg/kg	≤ 6.0 mg/kg (standard)
Soil cadmium (Cd) concentration	0.018 ± 0.001	mg/kg	≤ 0.7 mg/kg (standard)
Soil cobalt (Co) concentration	0.31 ± 0.1	mg/kg	≤ 5.0 mg/kg (standard)
Soil chromium (Cr) concentration	0.060 ± 0.001	mg/kg	≤ 6.0 mg/kg (standard)
Soil nickel (Ni) concentration	0.81 ± 0.01	mg/kg	≤ 4.0 mg/kg (standard)

Source: compiled by the authors on the basis of data from Resolution of the Cabinet of Ministers of Ukraine No. 1325 (2021)

As shown in Table 2, the levels of mobile lead, cadmium, cobalt, chromium and nickel in the soils of the agricultural land under study are higher than background values. However, all indicators remain significantly below the maximum permissible concentration standards.

Therefore, even in the absence of exceedances of the standard values for pollutants, military actions lead to complex disruptions in the functioning of agroecosystems, including the environmental consequences of agro-landscape transformation. This is consistent with

the conclusions of A. Santini *et al.* (2023), who emphasised the importance of analysing biological invasions. They noted that disrupting the ecological integrity of agro-landscapes through explosions and destroying the fertile layer significantly complicates the process of natural recovery and compounds threats to biodiversity. The results of the study correlate with the conclusions of M.J. Lawrence *et al.* (2015), who found that military action significantly reduces biodiversity and worsens the ecological condition of land, resulting in long-term consequences for agriculture. The results also confirmed the conclusion regarding the negative impact of mechanical soil compaction caused by heavy machinery and chemical contamination, which reduces the land's ability to recover naturally. This is consistent with the findings of A.B. Rexhepi *et al.* (2023), who confirmed a significant economic decline in Ukraine's agricultural sector during the war, due to reduced sown areas and falling productivity in agricultural enterprises. The Ukrainian government has launched a programme to recover the agricultural sector. Under this programme, investments totalling more than USD 5 billion are planned for the repair of damaged infrastructure, particularly irrigation systems, and for land reclamation. The programme also involves the government providing concessional loans to farms to help them restore production, at a maximum rate of 5-7% (National Bank of Ukraine, 2025).

A study by M. Khan (2022) highlighted the environmental consequences of war and conflict, particularly with regard to soils and natural resources. P. Broomandi *et al.* (2020) indicated that soil contamination by heavy metals reduces fertility and affects ecological systems, particularly in war zones. As M. Khan's study noted, these changes pose long-term risks to ecosystems

and agricultural productivity, both of which are crucial for the post-war restoration of land in Ukraine. D. Rawtani *et al.* (2022) focused their work on the environmental damage caused by the war in Ukraine, particularly the contamination of soils and water resources by heavy metals and toxic substances. They also emphasised that the resulting decline in soil fertility from hostilities and explosive munitions poses serious threats to food security. The present study confirms this, recording elevated concentrations of heavy metals such as lead, cadmium and arsenic in agricultural soils, thereby limiting their suitability for agricultural activity. L. Chai *et al.* (2024) analysed the impact of war on the global expansion of agricultural land and biodiversity. The findings point to possible changes in global agricultural landscapes, which could affect Ukraine through changes in agri-food networks and the adaptation of agriculture to new conditions. This is supported by the present findings, which note that environmental losses, particularly through land degradation, may make it more difficult to restore production and alter global food flows. B. Chen *et al.* (2024) assessed the impact of military actions on agricultural production in eastern Ukraine, identifying a significant reduction in cultivated areas and a decline in productivity. This is an important component of the present analysis, in which it was calculated that more than 30% of agricultural land remained unused due to hostilities, resulting in substantial economic losses. At the same time, their conclusions confirm the need for international assistance and state support to restore the agricultural sector in the post-war period. The assessment of agroecosystem biodiversity involved determining the microbiological activity of soils and the abundance of saprophytic organisms in both intact and damaged areas (Table 3).

Table 3. Assessment of soil biodiversity in control and damaged plots

Plot	Shannon index (H')	Simpson index (D)	Number of saprophytic organisms (CFU/g)
Kharkiv region (control)	3.5	0.92	2.3×10^6
Kharkiv region (damaged)	2.1	0.87	1.1×10^5
Zaporizhzhia region (control)	3.4	0.90	2.0×10^6
Zaporizhzhia region (damaged)	2.0	0.85	1.0×10^5

Table 3, Continued

Plot	Shannon index (H')	Simpson index (D)	Number of saprophytic organisms (CFU/g)
Kyiv region (control)	3.7	0.96	2.8×10^6
Kyiv region (damaged)	3.4	0.93	2.2×10^6

Note: for the assessment of soil biodiversity, samples were taken from control and damaged plots in Kharkiv and Zaporizhzhia regions; Luhansk, Donetsk and Mykolaiv regions were not included in the study because of restricted access to these regions during active hostilities or because of insufficient reliable data for comparison

Source: compiled by the authors

The evaluation results showed that the Shannon index reached $H' = 3.5$ in control plots that had not experienced significant mechanical or chemical damage, indicating high organism diversity. By contrast, the index was significantly lower ($H' = 2.1$) in plots damaged by hostilities in the Kharkiv and Zaporizhzhia regions. Meanwhile, within the studied territories of the Vyshhorod district in the Kyiv region, a slight reduction in the number of saprophytic microorganisms was observed, suggesting recovery processes and lower intensity of hostilities. Damage to the soil cover created preconditions for long-term weakening of the natural recovery potential of agricultural land. Without the application of special remediation measures, it was found that degraded soil components may remain unsuitable for agricultural use for many years. The results confirm substantial environmental damage to Ukrainian agricultural land caused by the mechanical compaction of soils by heavy machinery and chemical contamination by heavy metals. Significant damage to agricultural land and degradation of the natural environment lead to substantial economic losses affecting Ukraine's agricultural sector. According to World Bank data from 2023, the decline in yields caused by soil contamination and loss of fertility resulted in a 15-20% reduction in agricultural production volumes. The cost of restoring agricultural land degraded by military action is estimated at over USD 4 billion.

Economic losses in the agricultural sector resulting from the destruction of infrastructure and the loss of productivity

The economic consequences of military action on Ukraine's agricultural sector have manifested in a variety of ways, broadly categorised as

direct and indirect losses. Direct losses include the physical destruction of crops resulting from fires, explosions, and the movement of military equipment; damage to material and technical resources and infrastructure; and the theft of agricultural machinery. Indirect losses, meanwhile, encompass a decline in enterprise productivity, loss of investment attractiveness, and growing bankruptcy risks. Hostilities resulted in part of the sown area becoming inaccessible for cultivation, substantially reducing the gross harvest of grain and oilseed crops, which had traditionally formed the basis of Ukrainian exports. According to the Food and Agriculture Organization of the United Nations (FAO): Food Security (2024), around 30% of sown areas in the eastern and southern regions of Ukraine were unused in 2022, amounting to over 4 million hectares. Calculations show that crop losses in Ukraine caused by hostilities exceeded USD 4 billion. Ukraine suffered considerable economic losses as a result of armed aggression, particularly in the agricultural sector, which was affected by infrastructure destruction and declining productivity. D. Andrienko *et al.* (2024) noted that the indirect financial losses to the economy caused by the war exceeded USD 1.164 trillion, USD 83.1 billion of which was related to the agricultural sector and included the destruction of agricultural machinery, as well as damage to land and infrastructure. This has led to a significant decrease in agricultural productivity and investment attractiveness. Therefore, effective strategies are required to restore infrastructure and modernise agricultural production in order to rebuild the agricultural sector and ensure food security. The economic consequences have also been confirmed by the findings of the study by R.P. Tucker & J.R. McNeill (2025), which

described the economic losses caused by war. Damage to grain storage facilities, destruction of agricultural machinery, and demolition of irrigation systems made the recovery of agricultural production more difficult.

A significant aspect of these direct losses was the destruction of agricultural enterprises, machinery and infrastructure for storing and transporting harvested crops. In particular, more than 100 grain storage facilities and elevators were damaged or destroyed in the Kharkiv, Mykolaiv and Zaporizhzhia regions, with a combined storage capacity of over 2 million tonnes of grain. This resulted in double losses: a decline in yields and the loss of the ability to store and export products that had already been harvested (FAO Ukraine: Food Security..., 2024). According to agricultural associations, thousands of tractors, combine harvesters, and other specialised machinery were damaged, destroyed, or stolen in territories where hostilities took place, as well as in occupied areas. The total value of such losses is estimated to be in the hundreds of millions of US dollars. An additional factor was the loss of irrigation infrastructure. The destruction of the Kakhovka Hydroelectric Power Plant in 2023 caused water levels in the North Crimean Canal and the Kakhovka Canal to fall sharply, making it impossible to irrigate more than 500,000 hectares of agricultural land in southern Ukraine. This resulted in long-term yield losses, as the average productivity of these areas declined two to threefold without irrigation (Farming Amidst a War..., 2023; Klimentov, 2025). As the agricultural sector is a key part of Ukraine's economy, accounting for around 13% of total gross domestic product (GDP) prior to the war, active hostilities have led to a sharp fall in GDP. In particular, agricultural production declined by 20-25% in 2022-2023 due to military actions, resulting in a 3-4% reduction in the sector's share of GDP. These losses include lower yields, causing a reduction in the production of grain, oilseeds, and other important agricultural crops.

There was also a decline in the country's overall economic growth, which in 2022 amounted to only 3.2% of the pre-war level (World Bank, 2023). Indirect losses included a fall in the productivity of agricultural enterprises. From 2022 to 2023, agricultural production

declined by an average of 15-20% compared to pre-war levels. This was caused not only by a reduction in sown areas, but also by shortages of resources: fuel prices increased fivefold in 2022, there were disruptions in the supply of mineral fertilisers and plant protection products, and it was difficult to attract labour due to mobilisation and migration processes. Declining production volumes and high risks caused a sharp fall in the investment attractiveness of agribusiness. In 2022, private investment in Ukrainian agriculture fell by around 40%. This hindered the implementation of modernisation programmes, the purchase of new machinery, and the adoption of innovative technologies. Financial instability also led to a significant increase in the risk of enterprise bankruptcy (World Bank, 2023). According to OECD (2023) estimates, more than 30% of small and medium-sized farms ceased operations due to a lack of access to sales markets, damaged logistics routes, and reduced credit opportunities. Large agricultural holdings were also placed in a high-risk zone since blocking seaports and increasing export costs resulted in losses for companies with diversified assets. The war also had a significant impact on the financial stability of agricultural enterprises. As most farms rely on imported mineral fertiliser and fuel, the 2.5-fold increase in the price of these resources in 2022 reduced their profit margins. Farmers began to spend considerably more on logistics and ensuring production safety in their cost structure of production, which increased total enterprise costs by 30-40%. These factors caused a significant decline in the profitability of agricultural enterprises. Total economic losses in the agricultural sector caused by the war exceed USD 10 billion, with the largest share accounted for by losses resulting from declining yields, damaged infrastructure, and destroyed agricultural machinery. Losses caused by soil degradation, reduced production capacity, and a decline in investment attractiveness account for a significant proportion of these losses. By way of comparison, the agricultural sector generated over USD 20 billion in export revenues in 2021, accounting for around 15% of the country's total exports (State Statistics Service of Ukraine, 2023). Thus, the economic losses to the agricultural sector were complex in nature. Direct losses in the

form of destroyed crops, damaged infrastructure and lost machinery were combined with indirect losses, including declining productivity, reduced investment and growing bankruptcy risks. Taken together, these factors pose long-term threats to the recovery of agricultural production and require systematic state support, international assistance, and the implementation of anti-crisis management strategies.

Socio-economic impact of the war on agriculture in Ukraine

The study by T. Ben Hassen & H. El Bilali (2022) emphasised that the war in Ukraine had serious consequences for global food security, creating threats to sustainable and resilient food systems worldwide. I. Liadze *et al.* (2023) highlighted the economic costs of war, manifested through reduced production capacity and resource losses. According to I. Liadze *et al.*, the principal economic losses were the destruction of agricultural infrastructure, the reduction in sown areas, and lower yields as a result of hostilities, which led to significant financial losses. Similar conclusions were presented in the work of J. Bluszcz & M. Valente (2022), which focused on the economic costs of hybrid warfare. H. El Bilali & T. Ben Hassen (2024) found that the war affected global food systems by disrupting crop production cycles and the distribution of food resources. H. Hussein & M. Knol (2023) emphasised the impact of the war on global food trade networks, further complicating the supply of agricultural products to international markets. Studies by S. Musisi & E. Kinyanda (2020) and J. Nyssen *et al.* (2023) have emphasised the long-term consequences of war, including post-traumatic stress disorder (PTSD) among civilian populations in African communities. The lack of seasonal workers in combat zones complicated land cultivation and harvesting processes significantly. The socio-economic consequences of the war for the agricultural sector manifested in three key ways: deterioration of food security; increased household spending on food; mass migration of the rural population; reduction in labour potential; and increased business risks alongside restricted access to financial resources. Military action had a significant impact on the domestic food market. The blocking of

exports through seaports, the mining of territories, and the reduction in cultivated areas led to shortages of certain goods and a significant increase in food prices. Following the blocking of the main seaports on 24 February 2022, Ukraine lost the ability to export more than 90% of its agricultural goods by sea. By the end of 2022, grain exports had fallen by 57% and oilseed exports by 42%, compared to 2021 (Copernicus-enabled Assessment, 2023). This blockade caused serious shortages of wheat, maize and sunflower oil on international markets, significantly increasing global prices for these products. Wheat prices, for example, rose by 58% in 2022, while maize and sunflower oil prices increased by 30-40% (World Bank, 2023). Ukraine's domestic market also underwent significant changes due to the blocking of export routes and declining production. According to the State Statistics Service of Ukraine (2024), consumer food prices rose by an average of 35-40% in 2022, including bread (37%), vegetables (52%) and poultry meat (28%). This resulted in household expenditure on food increasing by around 20% of family budgets, particularly in rural areas where incomes were below the national average. Ukraine's food security declined substantially, falling 13 places in the Global Food Security Index between 2021 and 2022 (Country Report: Ukraine, 2022).

One consequence of the conflict was large-scale population migration. According to the 2023 Food Security and Livelihoods report, more than 6.5 million Ukrainians had left the country by the end of 2022, while the number of internally displaced persons exceeded 5 million. A significant proportion of these individuals had lived in rural areas, directly reducing the labour resources available to the agricultural sector. Labour shortages were reflected in a deficit of seasonal workers for harvesting, resulting in direct losses of agricultural produce. Furthermore, the outflow of young and working-age individuals diminished the prospects of restoring agricultural production once the active phase of hostilities had ended. Business conditions for agricultural enterprises became substantially more difficult, particularly as banking institutions reduced lending to the agricultural sector due to the high risk of non-repayment. According to estimates by the National Bank of

Ukraine, lending to agribusiness fell by 45% in 2022 compared with the pre-war period. The situation was further complicated by rising interest rates, with the average short-term loan rate for farmers increasing from 14% in 2021 to 24% in 2022. Access to international investment was also restricted. According to the World Bank, foreign investment in Ukrainian agriculture fell by almost 40% in 2022. Additionally, the cost of insuring agricultural risks increased, and

insurance companies often refused to conclude contracts due to the uncertain situation. This led to financial instability among farming enterprises and increased the risk of bankruptcy, particularly for small and medium-sized businesses, of which more than 30% were forced to suspend operations (World Bank, 2023). To analyse the risks that agricultural enterprises will face in the post-war period comprehensively, the categorisation of risks presented in Table 4 can be used.

Table 4. Risk analysis for agribusiness

Risk category	Description	Examples of potential threats
Economic risks	Risks associated with economic instability and reduced productivity	Reduced investment attractiveness, rising raw material prices, exchange rate fluctuations
Environmental risks	Risks associated with soil degradation and environmental contamination	Land damage due to heavy metal contamination, changes in ecosystems, decline in soil fertility
Social risks	Risks associated with population migration and changes in labour potential	Loss of workforce, high level of rural out-migration, reduction in the number of workers in the agricultural sector
Logistical risks	Risks associated with damaged infrastructure and disruptions in supply chains	Destruction of logistics routes, blocking of ports, restricted access to irrigation systems

Source: compiled by the authors on the basis of World Bank (2023), FAO Ukraine: Food Security... (2024), The Ministry of Agrarian Policy presented... (2024)

As shown in Table 4, the risks are complex in nature and may affect the financial stability of enterprises, production productivity, labour availability and infrastructure effectiveness. This classification provides a foundation for targeted risk management and the development of strategies to minimise potential negative impacts on agribusiness. Thus, the socio-economic impact of the war on agriculture was characterised by systemic losses. Food security deteriorated, reflected in rising prices and household expenditure. The migration of the rural population reduced the labour potential of agricultural production, while financial constraints and high business risks prevented enterprises from functioning and developing stably. These factors combined to increase the vulnerability of the agricultural sector, requiring comprehensive state support measures, international assistance and long-term recovery programmes. The study's results confirm the significant impact of the war on Ukraine's agricultural sector, evident in environmental and economic losses as well as social consequences for food security and global agri-food networks.

Recovery opportunities and prospects for managing agribusiness in the post-war period

Once the active phase of military action has ended, the agricultural sector's primary task will be to restore land, natural resources and production potential. A key priority will be the reclamation of land that has been mechanically damaged, degraded or chemically contaminated. In de-occupied territories, surveys of soils were conducted, explosive hazards were removed and agrochemical analyses were carried out. According to a Copernicus assessment from 2023, more than 200,000 hectares of arable land were surveyed for their suitability for reuse between 2023 and 2024. Of this land, around 40% required deep reclamation before economic activity could resume. To restore soil fertility, bioremediation technologies, the local application of organic fertilisers and green manure crops were used, as well as chemical neutralisation methods where heavy metal concentrations exceeded permissible standards. For Ukraine to recover sustainably after the end of hostilities, it is crucial to rebuild infrastructure, reconstruct

old agricultural enterprises and modernise their technical base. The cost of restoring irrigation infrastructure in southern Ukraine alone is estimated at over USD 1.5 billion, while the total cost of restoring agricultural infrastructure exceeds USD 8 billion. Modernising the technical base includes renewing the agricultural machinery fleet, introducing energy-efficient solutions, and increasing the mechanisation of field operations (FAO Ukraine: Food Security..., 2024). The resilience of agricultural enterprises can be strengthened by diversifying production areas. This includes developing new crops that require fewer resources, such as water-efficient and drought-resistant varieties. Integrating livestock farming and horticulture is also important in order to reduce dependence on a single line of activity and improve the economic stability of agricultural enterprises. A key aspect of financial stability is introducing insurance mechanisms for farmers. Insurance against risks such as natural disasters, war, and other unforeseen circumstances would mitigate financial losses and enable agricultural enterprises to recover from crises. Both public and private insurance products must be introduced to increase the sector's resilience. Using innovative digital technologies for agribusiness management would significantly reduce costs and improve production efficiency. Precision farming systems and digital platforms for monitoring soil and crop conditions would allow enterprises to optimise operations, reduce costs and integrate into global supply chains. Public-private partnership models involving cooperation between the state and the private sector could be an effective means of implementing large-scale infrastructure recovery projects and ensuring access to finance. This could include financing the restoration of irrigation systems, creating new logistics networks, and developing agricultural infrastructure. These measures would help to improve production efficiency and reduce costs. This study developed recommendations for increasing the resilience of agricultural enterprises, particularly through diversifying production areas, introducing insurance mechanisms, and using digital technologies. These recommendations were developed based on an analysis of the current situation in Ukraine's agricultural

sector, as well as international research and best practices for adapting agricultural enterprises to crisis conditions.

Innovative technologies and digital solutions have become key to improving the effectiveness of post-war recovery. In practice, precision farming systems and satellite and unmanned monitoring of soil conditions and crops are being implemented. These technologies were also recommended in studies by A. Bhardwaj & H. Parveen (2024), which suggest that the efficiency of agricultural production could be significantly improved through innovative solutions. The findings of A.B. Avagyan (2021) are consistent with the conclusions of the present study regarding the environmental impact of military activities on agricultural land. Particular attention was given to land recovery mechanisms through bioenergy processes and bioremediation technologies, as discussed in both studies. Geographic information systems should also play an important role in mapping the level of land degradation and planning recovery measures. Using digital platforms would enable agricultural producers to optimise management processes, reduce production costs, and integrate into global supply chains. According to the World Bank's (2023) estimates, introducing digital solutions into restored agricultural enterprises would increase productivity by an average of 15-18% in the first years following integration. State support, international assistance and investment also played an important role in shaping resilient management strategies. Ukrainian government programmes provided for concessional loans and grants for farmers to restore production. Under the "Affordable Loans 5-7-9%" initiative, the National Bank of Ukraine (2025) provided agricultural enterprises with financing at subsidised rates, which partly compensated for limited access to banking resources. FAO Ukraine: Food Security... (2024) allocated more than USD 1 billion in 2022-2024 to support the agricultural sector in the form of technical assistance, equipment and financial grants. In addition, the European Union launched the Ukraine Facility programme, which provided long-term financing for the modernisation of agriculture and its integration into the European agricultural space

(Strategic Orientations of the Ukraine..., 2024). Thus, opportunities for restoring agribusiness were formed at the intersection of three interrelated directions: land reclamation and infrastructure restoration, the introduction of innovative technologies and digital solutions, and the development of mechanisms for state support and international investment. The combination of these factors created the pre-conditions not only for rebuilding agricultural production, but also for transforming it into a

more resilient and competitive model of development. The synthesis of the results made it possible to systematise the main consequences of military actions for Ukraine's agricultural sector into four interrelated blocks: environmental losses, economic losses, socio-economic consequences, and recovery opportunities. Such a structure makes it possible to assess not only the scale of the degradation of agricultural resources, but also the potential for their recovery in the post-war period (Table 5).

Table 5. Comprehensive consequences of the war for Ukraine's agricultural sector

Results block	Main indicators	Consequences for agribusiness
Environmental losses	200,000 ha of damaged land; 20% of the most fertile land taken out of use; lead ↑ threefold, cadmium ↑ 2.5-fold	Reduction in the area of agricultural land, decline in soil fertility, soil contamination, risks to public health, deterioration in environmental quality, disruption of ecological balance, decline in biodiversity
Economic losses	-4 million ha of crops; > 2 million tonnes of losses in grain storage; 500,000 ha without irrigation; -15-20% productivity	Crop losses, decline in the value of produce due to lower quality, losses of agricultural machinery, reduced investment, increasing bankruptcy rates
Socio-economic consequences	Prices +35-40%; 6.5 million refugees; lending -45%; SMEs -30%	Deterioration of food security, labour shortages, financial instability
Recovery opportunities	200,000 ha surveyed; need for USD 8 billion in recovery; productivity ↑ by 15-18% owing to digital technologies	Reclamation, modernisation, innovation, state and international support

Source: compiled by the authors on the basis of Copernicus-enabled assessment... (2023), Food Security and Livelihoods (2023), FAO Ukraine: Food Security... (2024)

Analysis of the summary data revealed that the consequences of the war were multi-level in nature, ranging from physical land degradation and infrastructure losses to socio-economic challenges that undermined agribusiness resilience. At the same time, the table shows that there is substantial potential for recovery based on reclamation, the introduction of innovative technologies, and attracting investment. Combining these factors laid the groundwork for a new management model for the agricultural sector, which aimed to not only reconstruct the sector, but also enhance its competitiveness in the post-war period. According to the analysis, hostilities caused significant soil degradation, heavy metal contamination and destruction of agricultural infrastructure, creating long-term risks to food security and economic stability.

Using modern technologies to monitor and assess land conditions is key to determining the scale of losses and planning recovery measures. The results obtained confirm the conclusions of S. Ulihanets *et al.* (2025), who demonstrated the negative impact of fire and military action on natural ecosystems, including soil and water contamination. The assessment of saprophytic microorganism abundance and the Shannon index correspond to the concept proposed by W. Leal Filho *et al.* (2024) regarding soil ecosystem degradation processes and their connection with agricultural activity and regional land resource stability. Mapping destruction based on satellite data, as proposed by O. Dietrich *et al.* (2024), enabled the spatial distribution of damaged land and the extent of heavy metal standard exceedances to be refined, which is

important for determining economic losses and recovery priorities. The partial preservation of soil quality in the Kyiv region suggests the impact of local agronomic practices and the time interval between the onset of hostilities and sample collection. This is consistent with the concept of gradual changes in land structure, as evidenced by satellite image time series, as noted by S. Holail *et al.* (2024). A comparison with the analysis by Y. He *et al.* (2025) demonstrated the effectiveness of multi-level monitoring and the integration of satellite data in assessing long-term environmental consequences of hostilities. This confirms the suitability of applying similar methods to Ukrainian territories. A comprehensive assessment of the economic and socio-economic consequences enables more informed decisions to be made regarding the restoration of agricultural infrastructure and the planning of land reclamation measures.

CONCLUSIONS

The study enabled a comprehensive assessment of the environmental, economic and socio-economic consequences of military action on agricultural land and Ukraine's agricultural sector. It identified damage to over 200,000 hectares of land, around 20% of which was the most fertile land taken out of use. Significant exceedances of permissible heavy metal concentrations in the soils of the Kharkiv, Luhansk and Zaporizhzhia regions were identified. Substantial exceedances of standard values were recorded: lead by three times, cadmium by 2.5 times, arsenic by twice, nickel by more than twice and zinc by 1.6 times. This creates long-term risks to public health and makes it impossible to obtain safe, high-quality crop products. Within the agricultural land of the Kyiv region, elevated levels of cadmium, cobalt, nickel, lead and chromium were recorded compared to background values. However, no exceedance of standard indicators was identified. This can be explained by the selective impact on soils, the partial disturbance of their integrity, the application of agronomic measures involving the filling of craters with clean soil and the considerable time interval since the damage occurred. In Kharkiv and Zaporizhzhia regions, the assessment results

showed that in control plots that had not experienced significant mechanical or chemical damage, the Shannon index reached $H' = 3.5$, indicating high organism diversity. By contrast, in plots damaged as a result of hostilities, the index was significantly lower ($H' = 2.1$). In the Kyiv region, a decline in the content of saprophytic microorganisms was observed, with $H' = 3.7$ in control plots and 3.4 in damaged plots. This indicates recovery processes and lower intensity of hostilities in these areas.

Significant economic losses result from a decline in the natural recovery potential of land, soil contamination, increased concentrations of heavy metals in soils, and the inability to produce safe, high-quality agricultural products. Economic losses caused by military action included the loss of more than 4 million hectares of crops, the destruction of machinery and storage facilities, and damage to irrigation systems. Yields declined two- to threefold. Indirect losses are reflected in a 15-20% reduction in production, rising resource costs, and the suspension of activities by over 30% of small and medium-sized farms. Socio-economic consequences included a 35-40% increase in food prices, higher household expenditure, the migration of more than 6.5 million people and restricted access to credit. However, a significant recovery potential has been identified: the estimated cost of recovery is more than USD 8 billion, and modernising the technical base and introducing digital technologies could increase productivity by 15-18%. Further research should focus on developing methods for assessing damage to agricultural enterprises caused by military action, models of the long-term resilience of the agricultural sector and the effectiveness of reclamation measures and the implementation of innovative technologies in the post-war period.

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Еколого-економічні підходи до визначення збитків, завданих сільськогосподарським угіддям воєнними діями

Анотація. Метою статті було оцінити еколого-економічні наслідки воєнних дій для сільськогосподарських угідь України та визначити основні еколого-економічні показники для оцінки впливу воєнних дій на довкілля з подальшою можливістю відновлення аграрного бізнесу в післявоєнний період. Дослідження базувалося на комплексному аналізі екологічних, економічних та соціальних наслідків воєнних дій для аграрного сектору України із використанням польових обстежень, супутникових даних, лабораторних аналізів ґрунту та офіційної статистики. Встановлено, що внаслідок бойових дій понад

200 тис. гектарів сільськогосподарських земель зазнали ушкоджень, з них близько 20 % найродючіших угідь виведено з обігу, при цьому у Харківській, Донецькій, Миколаївській, Луганській та Запорізькій областях зафіксовано перевищення нормативів важких металів у ґрунті: свинець – у 3 рази, кадмій – у 2,5 рази, арсен – у 2 рази, нікель – більш як у 2 рази та цинк – в 1,6 рази. У свою чергу, на досліджуваних сільськогосподарських угіддях у межах Вишгородського району Київської області не було зафіксовано перевищення гранично допустимої концентрації рухомих форм важких металів, зокрема свинцю, кадмію та ін. Зафіксоване значне перевищення фонових рівнів важких металів у ґрунтах створює довгострокові ризики для якості та безпечності продовольчої продукції, економічних збитків і здоров'я населення, що підкреслює важливість моніторингу забруднення ґрунтів у зонах впливу бойових дій на сільськогосподарських підприємствах. Проведене дослідження показало, що прямі економічні втрати включали втрату понад 4 млн гектарів посівів, руйнування понад 100 зерносховищ загальною потужністю 2 млн тон, а також зниження врожайності на понад 500 тис. гектарів через відсутність зрошення. Непрямі збитки проявилися у скороченні виробництва на 15-20 %, зростанні цін на продукти харчування на 35-40 %, падінні обсягу інвестицій на 40 % та припиненні діяльності понад 30 % малих і середніх підприємств. Виявлено, що соціально-економічні наслідки охоплювали міграцію понад 6,5 млн осіб та погіршення продовольчої безпеки, проте досліджувана територія володіє також значним потенціалом відновлення

Ключові слова: деградація ґрунтів; аграрний сектор; витрати; продовольча безпека; державна підтримка