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Pollution Problems in the Economic Agricultural Sector: Evaluating the Impact on Natural Resources and Solutions for Improvement

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Abstract: In the face of modern global challenges and the growing impacts of anthropogenic activity, the issue of agricultural pollution of natural resources has become a critical issue, especially in countries experiencing ecological and social crises. Ukraine, as one of Europe's largest agricultural producers, faces unique challenges stemming from the legacy of radiation contamination following the Chornobyl nuclear disaster, intensive land use, and the environmental consequences of military conflict. Our study focuses on analyzing the sources of agricultural pollution, including chemical runoff, pesticides, herbicides, heavy metals, and nutrient leaching, as well as their impacts on the sustainability of agroecosystems, food security, and human well-being. The methodology is based on a systematic analysis of scientific research, agrochemical surveys, monitoring reports, and documents from governmental and non-governmental organizations. The assessment of natural resources was conducted using an integrated approach combining quantitative and qualitative pollution indicators. The results reveal an increasing threat to natural resources in Ukraine due to outdated technologies, radiation contamination, and military activities. Special attention is given to the need for a transition to agroecological farming methods and bioremediation for restoring contaminated lands and water resources. The study contributes to the development of sustainable approaches to managing natural resources and strategic measures to minimize agricultural pollution. The Ukrainian context underscores the relevance of research in countries with transitional economies and unique environmental challenges, making the findings significant for international scientific agendas and environmental policy. Future research perspectives include developing innovative technologies to prevent pollution and enhance the sustainability of agroecosystems to ecological challenges, as well as creating international resource management models based on Ukraine's experience.

Keywords: pollution; agroeconomy; natural resources; environmental changes; ecological challenges; sustainable agriculture; human well-being

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1. Introduction

Pollution refers to the introduction of physical, chemical, or biological elements into the environment that are atypical and detrimental to natural ecosystems and human health [1]. According to scientific sources, pollutants can be of both natural origin, such as volcanic ash, and anthropogenic origin, such as industrial waste, wastewater, and other human products [2,3].

According to the United Nations, pollution is the presence of substances and heat that, due to their quantity or location, cause undesirable environmental consequences [4].

Environmental pollution is one of the leading causes of disease and premature death in the world, causing more than nine million premature deaths each year, most of which are the result of air pollution. This number is significantly higher than deaths from diseases such as AIDS, tuberculosis, or malaria [5].

The modern agricultural sector faces significant environmental challenges related to the pollution of natural resources, which poses a serious threat to food security, quality of life, sustainability of agricultural systems, and long-term preservation of the natural environment [6]. Suffering from pollution coming from the industrial and municipal sectors of the economy, agriculture itself is becoming one of the main factors of environmental pollution, which covers all the main components of ecosystems: air, soil, and water. The application of agrochemicals, particularly N and P fertilizers, leads to excessive enrichment of soils and water systems with nutrients, which causes significant environmental issues, such as aquifer contamination and eutrophication of aquatic ecosystems [2,7]. This, in turn, contributes to the formation of hypoxic zones in water bodies [8], which adversely impacts aquatic flora and fauna, causing loss of plant and animal species diversity [8,9], as well as the quality of water for human consumption [10].

According to the UN Food and Agriculture Organization (FAO), approximately 2250 km^3 of wastewater is discharged into the environment each year, of which 330 km^3 is municipal wastewater, 660 km^3 is industrial wastewater (including cooling water), and 1260 km^3 is agricultural wastewater [11]. The ability of soils to preserve, buffer, and decompose pollutants entering water systems is being exceeded by intensive anthropogenic practices in the cultivation of arable land and pastures. This has resulted in widespread increases in N levels [12], salinity, and biological oxygen demand (BOD) in freshwater ecosystems.

A particular threat to the world's natural resources is currently the growing use of pesticides, which can accumulate in ecosystems and lead to the death of beneficial insects, pollution of water bodies, and the creation of persistent pollutants that affect human and animal health [2].

Agricultural pollution is a major environmental problem in many countries around the world. For example, in Europe, diffuse pollution from agriculture covers large areas where NO_3 from fertilizers enter groundwater, posing risks to drinking water quality and public health [13].

Currently, the European agricultural sector is recognized as being at risk. According to the EU LUCAS study, 80% of agricultural soils in the region contain pesticide residues. Additionally, the study found that 21% of European soils exceeded regulatory thresholds for heavy metals, such as Cd [14].

Among the various environmental challenges associated with contemporary agriculture, scientists emphasize the risks posed by genetically modified crops. While these crops are known to enhance yields and improve disease resistance, there are significant concerns regarding their potential impact on biodiversity, particularly through genetic drift and unforeseen environmental consequences [2].

These problems are particularly relevant in Ukraine, where additional environmental challenges are exacerbated by the consequences of the Chornobyl nuclear power plant accident and the ongoing military operations in the southeastern territories.

The aims of this article are as follows:

(1) To identify the most critical sources of natural resource pollution in Ukraine's agricultural sector, based on a systematic analysis of scientific research, monitoring data from non-governmental organizations, and governmental documents as well as to substantiate the destructive environmental consequences of their impact.

(2) To develop recommendations on strategic directions for restoring ecologically degraded and technologically polluted land, water resources, and environmental areas, taking into account regional pollution sources and types.

The study's theoretical value lies in its comprehensive and interdisciplinary approach to analyzing pollution in the agricultural sector, contributing to the understanding of critical pollution sources and their systemic effects on natural resources, ecosystems, and human health. By synthesizing findings from diverse scientific sources and incorporating the authors' own observations, this research advances the theoretical discourse on environmental degradation caused by agriculture. It also provides a framework for evaluating the effectiveness of agroecological and regulatory interventions aimed at mitigating pollution. Furthermore, the study highlights the interconnection of ecological, economic, and social factors, offering insights into the mechanisms by which pollution disrupts sustainability in agricultural systems.

The practical significance of this study lies in its focus on developing recommendations tailored to the specific environmental and socio-economic conditions of Ukraine. It emphasizes the urgent need to create state mechanisms for restoring ecologically degraded and technologically polluted agricultural land and water resources. The study highlights strategies for balancing short-term economic needs with long-term environmental sustainability, addressing issues such as pollution caused by agrochemicals and the consequences of military actions.

Particular attention is given to the development of practical approaches for implementing agroecological principles, enhancing land use practices, and promoting sustainable resource management. These measures aim not only at reducing environmental damage but also at ensuring the resilience of agricultural systems and food security in Ukraine, aligning with global sustainable development goals.

2. Materials and Methods

This study employs a comprehensive and interdisciplinary approach to assess the pollution of natural resources in Ukraine's agricultural sector. The methodology integrates data from scientific research, governmental and non-governmental monitoring reports, and regulatory documents to identify critical pollution sources, evaluate their impacts on ecosystems and human health, and propose strategic recovery measures.

The first step involved synthesis and analysis, where a wide range of literature, monitoring data, and expert reports were systematically reviewed to identify key pollution sources, such as heavy metals (e.g., Cd, Pb), radionuclides, pesticides, and NO_3. These pollutants were examined in terms of their distribution, intensity, and long-term effects. For instance, radionuclide contamination in the Polissia region was traced back to the Chornobyl disaster, while heavy metal pollution was linked to industrial and military activities in the southeast. This step enabled a comprehensive understanding of the causes and consequences of agricultural pollution.

Next, classification was employed to categorize pollution types and their associated impacts systematically. The study distinguished between primary (e.g., chemical discharges from industrial activities), secondary (e.g., eutrophication, acidification), and the resulting effects (e.g., loss of biodiversity, soil degradation). This classification framework was critical for identifying specific recovery methods tailored to each pollution type. For example, primary pollution from heavy metals required soil reclamation techniques, while secondary effects like eutrophication called for agroecological interventions.

The study utilized systematization to organize data from diverse sources into a cohesive framework. Data from government monitoring programs, research institutions, and international organizations were consolidated to map high-risk contamination zones. For instance, soil contamination data from the Ukrainian State Soil Protection Institution were integrated with regional monitoring results to provide a detailed understanding of pollution hotspots and their severity.

Finally, an integrated approach to restoration technologies was applied to evaluate the most effective recovery methods for various types of pollution. Technologies such as agroecological practices, bioremediation, and soil reclamation were assessed based on their efficiency and sustainability. For example, bioremediation using microorganisms and stress-tolerant plants was identified as a promising solution for addressing heavy metal contamination, while agroecological techniques were recommended for restoring soil fertility in areas impacted by chemical pollutants, such as NO_3.

These methodological steps formed the foundation for the results and discussion sections, enabling the development of strategic measures for ecological restoration and sustainable agricultural practices. The integration of synthesis, classification, systematization, and targeted restoration approaches ensured that the findings are regionally and contextually relevant while addressing the broader goals of environmental sustainability.

3. Results

Industrial enterprises exert considerable pressure on the natural resources of Ukraine's agricultural sector. Hazardous industrial emissions released into the atmosphere are concentrated and accumulated on the land directly adjacent to production facilities, disperse through the air over hundreds of kilometers from the emission sources and later fall to the Earth's surface with atmospheric precipitation, appearing in the form of acid rain, which has become a frequent phenomenon.

In the territories affected by industrial emissions, degradation of both natural and cultural biocenoses occurs, which leads to a decrease in the species composition, and numbers within the fauna are depleted. Additionally, the physical and chemical properties, as well as the biological activity of soils, deteriorate, resulting in acidification, decreased crop yields, and the accumulation of toxicants in agricultural products [15]. Numerous surveys have demonstrated that within the influence zone of industrial enterprises, the yield of grain crops decreases by 20–30%, while sunflower yields drop by 15–20%, vegetables by 25–30%, and fruits by 15–20% [16].

Industrial pollution in Ukraine is most prominent in the Donetsk and Kryvyi Rih basins, as well as in the Pavlohrad, Nikopol-Marhanets, and Kalush-Drohobych regions. These areas are characterized by the concentration of metallurgical, chemical, coal, and mining industries. The focus on extensive development and the application of outdated technologies became the main reason for their ecological crisis.

Intensive groundwater extraction, combined with the discharge of highly mineralized mine water and contaminated industrial wastewater, has led to a significant inflow of saline water into the rivers of Donetsk and Luhansk oblasts. This situation exacerbates the already negative environmental conditions in the region [6].

In western Donbas, mines extract water with a salinity ranging from 2 to 30 g/L, discharging it into the Samara River. The increased salinity in the river threatens soil salinization and the potential decommissioning of the local irrigation system. Similarly, in the Lviv–Volyn coal basin, water with a salinity of up to 3.1 g/L is pumped from mines and discharged into the Western Bug River [16].

In Kryvbas, highly mineralized mine water, with salinity levels ranging from level 30–40 to level 90–100 g/L, is discharged into the Ingulets River, leading to the salinization of extensive areas of irrigated land in Mykolaiv Oblast. An additional source of pollution in this region is the water generated during the dewatering of sludge ponds, which, in the form of mineralized runoff, enters the geographical grid and infiltrates underground aquifers, resulting in contamination.

Air pollution in mining regions is caused by emissions of solid and gaseous substances into the atmosphere that are generated during the development of mineral resources.

A significant ecological threat is the accumulation of waste dumps, particularly in the Donetsk and Kryvyi Rih basins, the area of which occupies more than 150 thousand hectares. Smoldering dumps release CO, SO_2, H_2S, and NO_x into the atmosphere. A substantial portion of the toxic waste generation comes from galvanic industries, which contain heavy metals. Waste in the Zaporizhzhya region contains Cr, Ni, Pb, and their compounds. In contrast, waste from the Donetsk region predominantly contains Co, Cu, Hg, Mn, and Zn.

Between 2016 and 2020, the State Institution "State Soil Protection", "Derzhgruntohorona" conducted a survey of approximately 8.6 million hectares of agricultural land in regions not affected by the military operations, specifically assessing mobile Pb compounds. Of the surveyed area, 38.5% exhibited mobile compounds within background levels (<0.8 mg/kg), while about 52% displayed low to moderate levels of contamination. Additionally, 8% of the area was found to have medium to elevated levels, and approximately 1.5% showed high to very high levels of contamination. The weighted average indicator with concentration of mobile Pb compounds in contaminated agricultural land was 1.59 mg/kg, indicating a moderate level of contamination with this chemical element (Figure 1).

The survey revealed that agricultural lands exceeding the maximum permissible concentration (MPC) of mobile Pb compounds (6 mg/kg) were found in Dnipropetrovska, Odesa, and Mykolaivska oblasts, with weighted average indicators for these contaminated areas were 11.76 mg/kg, 7.16 mg/kg, and 8.05 mg/kg, respectively [16].

Of the more than 8.5 million hectares of agricultural land surveyed, almost 49% of the land has a mobile Cd content that does not exceed background levels (<0.1 mg/kg). The contaminated area is about 4.4 million hectares and the weighted average indicator is 0.2 mg/kg of soil, which corresponds to a moderate level of contamination. The weighted average indicator of the content of mobile Cd compounds in the soils of the Steppe is 0.21 mg/kg of soil, Polissia is 0.2 mg/kg of soil, and Forest-Steppe is 0.19 mg/kg of soil. The highest content of mobile compounds of this chemical element is observed in Dnipropetrovska (0.49 mg/kg), Lvivska (0.3 mg/kg), and Cherkaska (0.27 mg/kg) oblasts and is classified as moderate pollution. At the same time, the MPC for mobile forms of Cd (0.7 mg/kg) is exceeded in three regions on 49.3 thousand hectares of agricultural land. The contaminated area in the Dnipro region is 45.47 thousand hectares, in Odesa and Mykolaiv regions it is 3.31 and 0.5 thousand hectares and the weighted average indicators for the contaminated area above the MPC were 0.98 mg/kg, 0.9 mg/kg, and 0.71 mg/kg, respectively.

Figure 1. Content of mobile Pb compounds in Ukrainian soils. Source: [16].

Of the surveyed agricultural lands, almost 49% of the land contains mobile Cd compounds that do not exceed background levels (<0.1 mg/kg). The contaminated area is more than 50%. The highest content of mobile Cd compounds of this chemical element is observed in the Steppe zone (0.2–0.27 mg/kg) (Figure 2).

Figure 2. Content of mobile forms of Cd in Ukrainian soils. Source: [16].

The above-mentioned processes of pollution of natural resources have significantly intensified as a result of military operations in Ukraine, which began in the regions of the Donetsk basin and currently cover part of the territories of five eastern and southern regions.

In areas of military operations, surface and groundwater, air, and soil are subject to chemical contamination due to the release of substantial quantities of combustion products from munitions, as well as the destruction of military and civilian equipment, municipal infrastructure, chemical plants, fuel and lubricant warehouses, and liquid chemical fertilizers. The chemical pollutants resulting from these events include oils, heavy metals, nitroaromatic explosives, organophosphorus nerve agents, radioactive elements, etc.

Pollutants, remaining in the environment for a long time and being mobile, move through the food chains of biological organisms, posing a direct threat to human populations due to their toxicity, carcinogenicity, and mutagenicity.

According to the Ministry of Environment of Ukraine, as well as research by the World Bank, Kyiv School of Economics, SavEkoBot, and other non-governmental organizations, revealed that tens of thousands of fires have occurred since the start of hostilities. The combustion of petroleum products in large volumes releases CO_2, benzopyrene, SO_2, NO_x, gaseous and solid products of incomplete combustion of fuel, V compounds, sodium salts CO_2, and NO_x as one of the most active greenhouse gasses contributing to the greenhouse effect [17].

CO_2 and sulfur gasses interact with moisture in the atmosphere to produce acid precipitation. When combined with precipitation, sulfur is converted into dangerous sulfuric acid, which increases the soil acidity.

Vehicular traffic, the detonation of explosive munitions and other military operations lead to soil compaction, structural damage, reduced water, and air infiltration, and the development of anaerobic processes, all of which reduce land productivity and adversely affect crop development. Furthermore, the disturbance of the soil surface caused by military actions negatively impacts the biological crust, which plays a crucial role in soil stabilization.

The findings of scientific research complement the surveys conducted by non-governmental organizations and projects operating in the combat zone since the onset of the conflict in 2014. Data obtained from the Environment–Law–Human project [18] indicate that the concentration of heavy metals in soil samples collected from combat areas frequently exceeded background levels by factors ranging from 1.2 to 12 times. Additionally, according to the Center for Humanitarian Dialogue [19], Cd levels were 4.4 times higher and Pb levels were 1.2 times higher than the regional average [20].

Data obtained from a study conducted by the Siverski–Donetsk Basin Water Resources Administration in the conflict area indicated that background levels of Hg, V, Cd, and non-radioactive ^{90}Sr were exceeded by factors of 1.1 to 1.3 times.

Flooding of mines due to power outages and damage to equipment, which leads to the shutdown of mine water drainage systems, poses a significant threat to water resources. When mine water mixes with surface water, it contaminates the latter with Fe, chlorides, sulfates, and other mineral salts, as well as heavy metals.

Researchers from the Sokolovsky Institute of Soil Science and Agrochemistry and the Semenenko Institute of Geochemistry, Mineralogy, and Ore Formation of the National Academy of Sciences of Ukraine are continuously conducting localized studies on the pollution of natural resources. According to the results obtained, all types of pollution caused by chemical, physical, mechanical, and biological impacts are recorded on the lands affected by hostilities [21,22].

The authors of this article have systematized all types of pollution from the territories of hostilities and characterized their expected consequences based on the analysis of the surveys available at this stage (Figure 3).

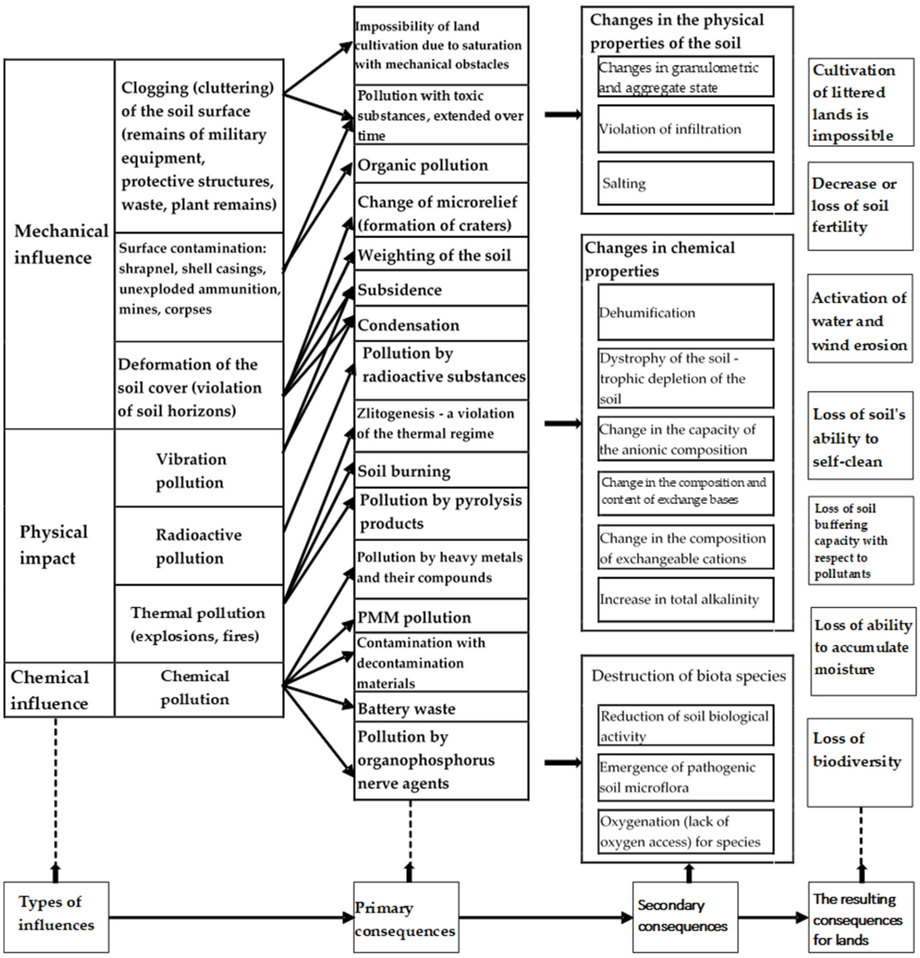

Figure 3. Types of impacts on soil from hostilities and their consequences. Source: Developed by the authors with the use of [21,22].

The restoration of land contaminated as a result of hostilities requires systematic legislative, regulatory, technological, and organizational measures, which is confirmed by foreign experience in implementing an integrated approach that takes into account environmental, social, and economic aspects [23]. In particular, such an approach may include the following:

- Conservation of contaminated land with its transfer on a lease basis to a state body established by law for the period of restoration;
- Reforestation of a part of the affected territories with the state buying them out from the landowner and withdrawing them from agricultural use;
- Reclamation of contaminated land with the introduction of ecologically sustainable farming methods.

The proposed technologies for soil reclamation of different types of contamination (Table 1) provide for the transition to agricultural activities based on agroecology, which is based on the imitation of natural processes and thus ensures beneficial biological interaction and synergy between the components of the agroecosystem [24,25].

Table 1. Technologies for soil remediation of various types of contamination.

№	Type of Pollution	Technology	Content of the Technology	Scenarios of Land Use
1	Subsidence, flooding	Drainage reclamation	Drainage works for groundwater drainage with subsequent treatment	Cultivation of perennial grasses, fodder crops; combination of intermittent furrowing and hollowing along with slotting and mowing; mulching (with manure, straw, forest floor, peat, stubble and post-harvest residues)
2	Drying, sealing	Irrigation reclamation	Water conservation measures and hydrotechnical methods of water supply and its transformation into soil moisture	Crop rotation; regular application of manure, compost, straw, other organic fertilizers, open trenches, loosening, and watering
3	Water erosion, secondary salinization, salinization and liquefaction, depletion and disruption of the organismal profile (explosion craters), pollution by products of the passage	Agricultural reclamation	Reducing surface runoff and transferring it to intra-soil runoff	Restoration by natural means or reforestation. For shallow craters up to 0.5–1 m, backfill with soil mass close to the natural horizons. Addition of gypsum, application of physiologically acidic and sulfur-containing fertilizers, introduction of perennial grasses into the crop rotation of perennial grasses. Slope terracing, contour plowing, selection of crops, proper tillage during plowing
4	Wind deflation and blowing away	Forestry reclamation	Reducing wind speed in the ground layer, returning lost nutrients to the soil	Sodding, soil-protective crop rotation in multi-depth cultivation (row crops and perennial grasses); tillage with flat cutters and sowing of grain crops with special stubble seeders
5	Threat of geochemical contamination, clogging (littering)	Cleaning of the territory	Mechanical cleaning of the surface, maintenance of sanitary condition	Measures to clean up toxic waste: use for any crops subject to quality control of agricultural products

Source: Developed by the authors using scientific developments and practice on this issue.

The authors recommend institutional and organizational measures to support environmentally sustainable and socially oriented restoration of disturbed and polluted natural resources. These measures should include:

- Development of a National Strategy for Post-War Soil Restoration of Disturbed Landscapes, taking into account the regional soil and geochemical conditions that affect natural resource use.
- Establishment of a Center for Environmental Management of Post-War Contaminated Areas to set pollutant standards and determine appropriate soil remediation levels.
- Development of zoning plans for post-war landscapes based on contamination levels and the necessary measures for recovery for normal economic activities; creation of a program for ecological and geochemical soil research; development of procedures for environmental and geochemical assessment of territories contaminated by substances of military origin.
- Development of a legal framework to provide a mechanism for the return of contaminated lands (with compensation to landowners) to state ownership for their restoration purposes and to provide investments to landowners for implementing land restoration measures. Establishing a guarantee of the rights of landowners in cases of temporary land conservation.
- Conducting soil certification of post-military operations landscapes.
- Implementation of pilot projects in contaminated areas to evaluate the effectiveness of rehabilitation measures on specific post-military operations lands.

The problem of contamination of natural resources in the agricultural sector is complicated by the consequences of the Chornobyl nuclear power plant accident. As a result of the explosion, radioactive contamination covered more than 8.4 million hectares, where 10 years later the density of Cs contamination still exceeded 0.1 Ci/km^2 [26]. The largest amount of contaminated land up to 70% is located in the Zhytomyr region. In the Kyiv region, contamination has spread to the northern regions (15% of the territory). In the Rivne, Volyn, Chernihiv, Vinnytsia, Cherkasy, Ternopil, and Ivano-Frankivsk regions, contamination occurred in the form of radioactive spots of different configurations and sizes (Figure 4).

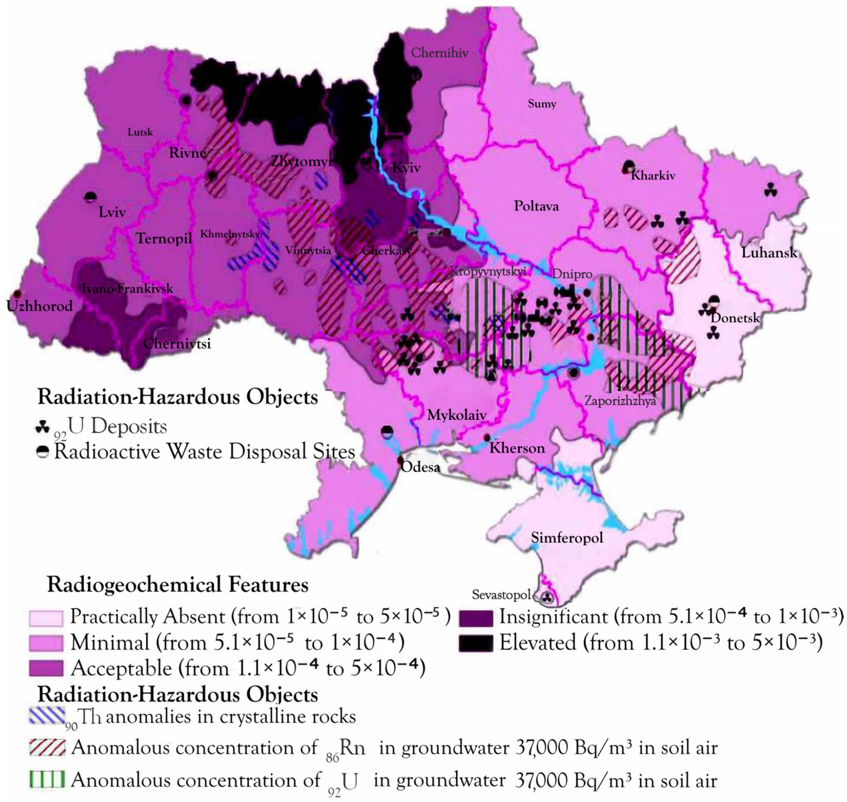

Figure 4. Conventional anthropo-ecological risk assessment based on the total density of radiation contamination of the territory (conventional units). Source: [27].

Thirty-five years after the Chornobyl accident, the content of ^{137}Cs in crop products in almost the entire contaminated area is balanced on the permissible limit or exceeds it. A certain increase in the level of contamination of products with ^{90}Sr is alarming, which is associated with an increase in its availability to plants [28].

Ecosystems are threatened by almost annual phenomena with increased frequency and intensity, such as dust storms, windstorms, heavy rains, forest fires, and fire storms, upward atmospheric flows that cause changes in the intensity of radionuclide migration across the country.

Over the period 1993–2020, more than 1800 local and large-scale fires occurred. The area of the "burns" exceeded 100,000 hectares. The radioactive ash formed as a result of the fires is actively involved in the geochemical migration of elements in ecosystems, causing uncontrolled contamination of lands remote from the zone. At the same time, burnt ash contains 600–180,000 Bq/kg of ^{90}Sr and from 4100 to 270,000 ^{137}Cs. In 2020, forest fires released 700 GBq of ^{137}Cs deposited by wood. As a result, uncontrolled areas with excessive radiation background are created.

With rising temperatures due to climate change and insufficient attention to this issue within governmental structures, there is a risk of large-scale fires in contaminated areas with catastrophic consequences not only for Ukraine but also for the European continent as a whole.

According to the Land Conservation Procedure approved by the Cabinet of Ministers [29], areas contaminated by industrial activities, where it is not possible to produce clean products, are subject to conservation. However, in many radionuclide-contaminated areas, these lands are still cultivated and the products grown are subsequently sold.

Currently, the primary source of collective radiation exposure of the population (up to 95% of the total) is formed as a result of the consumption of food produced on radioactively contaminated land. However, the population is not provided with means of individual protection against radiation contamination, as well as dosimeters and other devices for assessing environmental contamination.

Concurrently, there is a consistent decline in the implementation of radiation protection measures within the affected regions. Efforts related to radioecological monitoring and the assessment of radionuclide content in agricultural products from areas impacted by the Chornobyl disaster are gradually being reduced.

There is currently no effective mechanism for coordination and stable collaboration between central and local executive authorities, as well as between the various agencies, scientific institutions, healthcare institutions, professional associations, and representatives of civil society engaged in implementing measures to neutralize radioactive contamination in affected areas and restore them for safe production and human habilitation.

The above information does not exhaust all the problems that have accumulated in the country as a result of radioactive contamination of large areas, which indicates the need for fundamental changes in the management of radio-ecologically contaminated land at all levels of the management system.

Scientists indicate that contaminated food will continue to be the primary source of radiation risk for the population in the long term. In this context, the need for effective radiation monitoring and control of radionuclide levels in agricultural products remains critical. Additionally, enhancing the efficiency of resources dedicated to the development and implementation of measures for comprehensive rehabilitation and rational use of contaminated land remains relevant.

The working group of the Committee on Agrarian and Land Policy of the Verkhovna Rada of Ukraine has prepared a draft law entitled "On Amendments to Certain Laws of Ukraine Regarding the Classification of Zones of Radioactively Contaminated Territories and the Provision of Information to the Public on Their Radiation Status" [29].

The purpose of the draft law is to improve legislation in the field of overcoming the consequences of the Chornobyl disaster while aligning with contemporary international standards for human radiation protection. Specifically, it aims to establish zoning for areas contaminated by the Chornobyl disaster and to create legal mechanisms that promote the sustainable development of agricultural land and the broader affected territories.

The Cabinet of Ministers of Ukraine should initiate a state-funded program to conduct a comprehensive radiological survey of radiation-contaminated areas. This survey aims to delineate the boundaries of radiation-critical zones, where agricultural production poses a risk of producing products that exceed established radionuclide content standards, and to assess the feasibility of land use. Additionally, it is essential to include a separate category for radionuclide-contaminated soils, complete with appropriate coordinate references, in the Public Cadastral Map of Ukraine.

Experts recommend establishing an electronic database of forest survey materials aimed at rehabilitating forests through the assessment of areas within forest blocks that have been designated as unconditional resettlement zones, where all forestry activities were prohibited [30].

The authors concur with the views of several scientists regarding the necessity to standardize the concept of revitalizing agro-food production on remediated radioactively contaminated lands in the Polissya region. This should be followed by the development of an implementation strategy grounded in scientific justification and multivariate simulation modeling of various scenarios of the development of agricultural production. The goal is to establish cost-effective, naturally regenerating agro-ecosystems that support safe food production.

The task of the concept is to restore and maintain the barrier function for radiation protection and environmental safety for the population. It also aims to facilitate social, economic, scientific, and technical development in the territories of the exclusion zone and the areas of unconditional (mandatory) resettlement, which have experienced the greatest radioactive contamination.

The restoration of farming in radioactively contaminated areas has distinct characteristics, particularly the necessity to minimize individual radiation doses to the population through the production of food products, and the content of radionuclide levels which will not exceed permissible limits (Table 2).

Table 2. Permissible levels of radionuclides in agricultural crops.

Corn		**Winter Wheat**		**Potatoes**		**Spring Barley**		**Legumes**	
kBq/m^2	**Ci/km^2**	**kBq/m^2**	**Ci/km^2**	**kBq/m^2**	**Ci/km^2**	**kBq/m^2**	**Ci/km^2**	**kBq/m^2**	**Ci/km^2**
286	7.7	182	4.9	500	13.6	154	4.1	25	0.7

Source: [31].

The transition to long-rotation grain with the introduction of legumes and green manure will contribute to reducing the accumulation of radionuclides in agricultural products. The planning of the set of crops must be carried out taking into account their characteristics for the accumulation of radionuclides, so that the norms of cesium accumulation do not exceed the permissible. For example, potatoes, which can be grown on sod-podzolic soil, have a low level of "perception" when the density level reaches 15 Ki/km, corn is sown at a rate of up to 7.7 Ki/km, and cereals—2.4–4.1 Ki/km.

Currently, biological methods for cleaning the soil from pollution are called bioremediation methods, which are characterized by high efficiency and non-toxicity, and have attracted a lot of attention. The methods are based on the ability of different groups of living organisms to decompose or accumulate pollutants (heavy metals, radionuclides, N, P, and organic compounds, etc.) in their biomass in the process of vital activity [32]. If the viability and species diversity of the natural microbiocenosis of the soil are restored, biological methods are effective, but the process is slow and lengthy [33].

According to the conceptual model [33] of the bioremediation of soils contaminated with heavy metals, the use of a class of biological methods of remediation of contaminated by industrial activities soils with their gradation into groups has been envisaged:

- Methods of biodegradation of pollutants using microorganisms;
- Methods of bioaccumulation by plants and/or redistribution of pollutants in the soil with simultaneous effect on biological and inorganic (mineral substances that are products of the destruction of rocks and are formed without the participation of living organisms) components of the soil, which leads to the optimization of its ecological state due to the increase in the content of organic matter and its binding by clay minerals as well the improvement of the structural state of the soil, trophic and gas regimes, properties of the soil system as a whole.

Currently, there are a sufficient number of patented methods of bioremediation of contaminated soils in Ukraine using technical oil crops, lawn grass, and stress-tolerant transgenic plants to the action of heavy metals [34–37].

For phytoremediation of technogenic contaminated and depleted soils, a biological product of complex action was developed, which was obtained from the culture liquid of Pseudomonas sp. PS-17 grown on an optimized nutrient medium, followed by sterilization of the resulting culture liquid and removal of cell precipitate [38].

The application of agrotechnical measures to restore the agroecological functions of soils provides additional reduction in the negative impact of radioactive pollution, which creates preconditions for returning part of the polluted lands to the production sphere.

Pesticide and NO_3 pollution causes great harm to the environment and human health.

The use of pesticides and agrochemicals in agriculture is a serious problem for most countries where agriculture is the leading sector of the economy. Their use creates a threat not only to soil ecology but also to water bodies, which are closely interconnected with soils and land. Soil contamination with pesticides and agrochemicals leads to the accumulation of toxic chemicals in groundwater that can pose a threat to human health [39,40]. As a result of their use, not only harmful organisms die, but also many useful species, which disrupts the existing balance of species numbers in specific populations.

Ukraine is dominated by rotationless, highly specialized agricultural production with a transition to monoculture, which, in the face of rising climate temperatures, contributes to the spread and accumulation of diseases, pests, and weeds and leads to a constant increase in the use of chemical plant protection products [41].

The majority of the 1000 registered pesticides and toxic chemicals authorized for usage are used in violation of the established rules and regulations. At the same time, in many cases, the rules are outdated. For example, spraying of pesticides is allowed, while according to the European Commission Directive 2009/128 EU, all EU member states have to prohibit this method of pesticide application. The European Union is taking steps to reduce and prohibit the use of pesticides in general [42,43].

Pesticides can accumulate in agricultural products, with which they enter the bodies of people and animals. About 90% of all fungicides, 60% of herbicides, and 30% of insecticides are carcinogenic.

Critical pesticide pollution is recorded in the soils of the Donetsk, Luhansk, Kherson, Sumy, and Khmelnytsky regions and excessive pesticide content in crop production is observed in the central regions of the country.

The problem of disposal of prohibited and unusable pesticides, the warehouses of which became “no man’s land” in the process of reorganization of collective agricultural enterprises and enterprises that serve them, remains unresolved.

However, the state does not ensure control over their storage and use. The State Service of Ukraine on Food Safety and Consumer Protection, which is responsible for these functions, does not have laboratories that can test the content of pesticides in water, air, and soil. Regional laboratory centers, which were previously subordinated to sanitary and epidemiological stations and performed control functions, have now been transferred to the Ministry of Health of Ukraine without specifying their functions. The harmfulness of pesticide use creates the need to adopt appropriate regulations to regulate the limits of their use. It is also important to impose restrictions on the use of these harmful substances. This is aimed at reducing the negative impact on agricultural land. Given the imperfections of the current Law of Ukraine "On Pesticides and Agrochemicals" [39], currently, draft law No. 4558 [40] on the improvement of state regulation in the field of the use of pesticides and agrochemicals has been submitted to the legislative body for consideration. It is assumed that the list of enterprises entitled to carry out state testing for the purpose of toxicological and hygienic assessment is determined by the Ministry of Health of Ukraine, not the State Service of Ukraine on Food Safety and Consumer Protection. The adoption of Draft Law No. 4558 will result in the approval by the Cabinet of Ministers of Ukraine of updated procedures for state testing of pesticides, and agrochemicals, their state registration and application in practice.

NO_3 pollution is a critical problem for Ukraine.

Ukraine uses mainly (up to 70%) surface water for drinking purposes, which does not meet the requirements of sanitary legislation. The share of industrial and household waste in NO_3 pollution of groundwater is 47%, agricultural use of land and fertilizers is 30–37%, livestock waste is 10%, and other sources are 7% [44].

The use of a growing number of synthetic N fertilizers leads to the accumulation of extremely harmful N in the soil. Part of it migrates within the soil profile and in the NO_3 form it leaches to the upper aquifers and accumulates in the groundwater. Significant levels of NO_3 in intensive farming are already found at a depth of 10 m. At the same time, diffuse pollution is still not systematically measured in the country [45].

During the study of NO_3 pollution of water supply sources in nine regions of Ukraine, only 25% of uncontaminated wells were found [46]. Environmental pollution of rivers is shown in Figure 5.

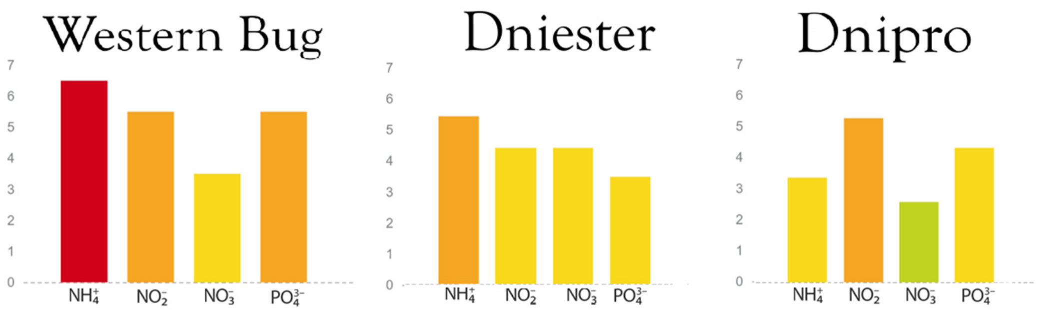

Figure 5. Environmental status of the main river basins of Ukraine by pollutant content. Source: [47].

One of the tools to solve the problem of such pollution is the implementation of the EU Nitrate Directive (Directive 91/676/EEC of 21 December 1991 on the protection of waters against pollution caused by NO_3 from agricultural sources). Its implementation, as demonstrated by the experience of EU countries, allows the reduction of water pollution caused by NO_3 and other nutrients from agricultural sources, as well as prevents such pollution in the future.

It provides for the development of a methodology for identifying areas vulnerable to NO_3 pollution and a Code of Best Agricultural Practices that would balance economic needs with the need to ensure good water and aquatic ecosystems.

Vulnerable zones are areas where the safe level NO_3 is already exceeded (over 50 mL/L), there are indications of eutrophication, or there are preconditions for it. Additional monitoring missions are carried out in such areas and Action Plans are applied to reduce risks and occurrences of pollution.

Codes of best agricultural practices include measures that establish rules for the storage of fertilizers, time, and space restrictions on their use in crop rotations, etc. Compliance with a set of these measures can prevent or significantly reduce the risks of NO_3 (or biogenic pollution in general) [48]. According to the European Commission, the implementation of the Nitrate Directive and good farming practices had a positive impact on the environmental situation in most EU member states. As a result, the concentration of pollutants began to decline in 70% of surface water bodies and 66% of groundwater. Simultaneously, in several countries, NO_3 accumulation surpasses permissible limits, as illustrated in Figure 6.

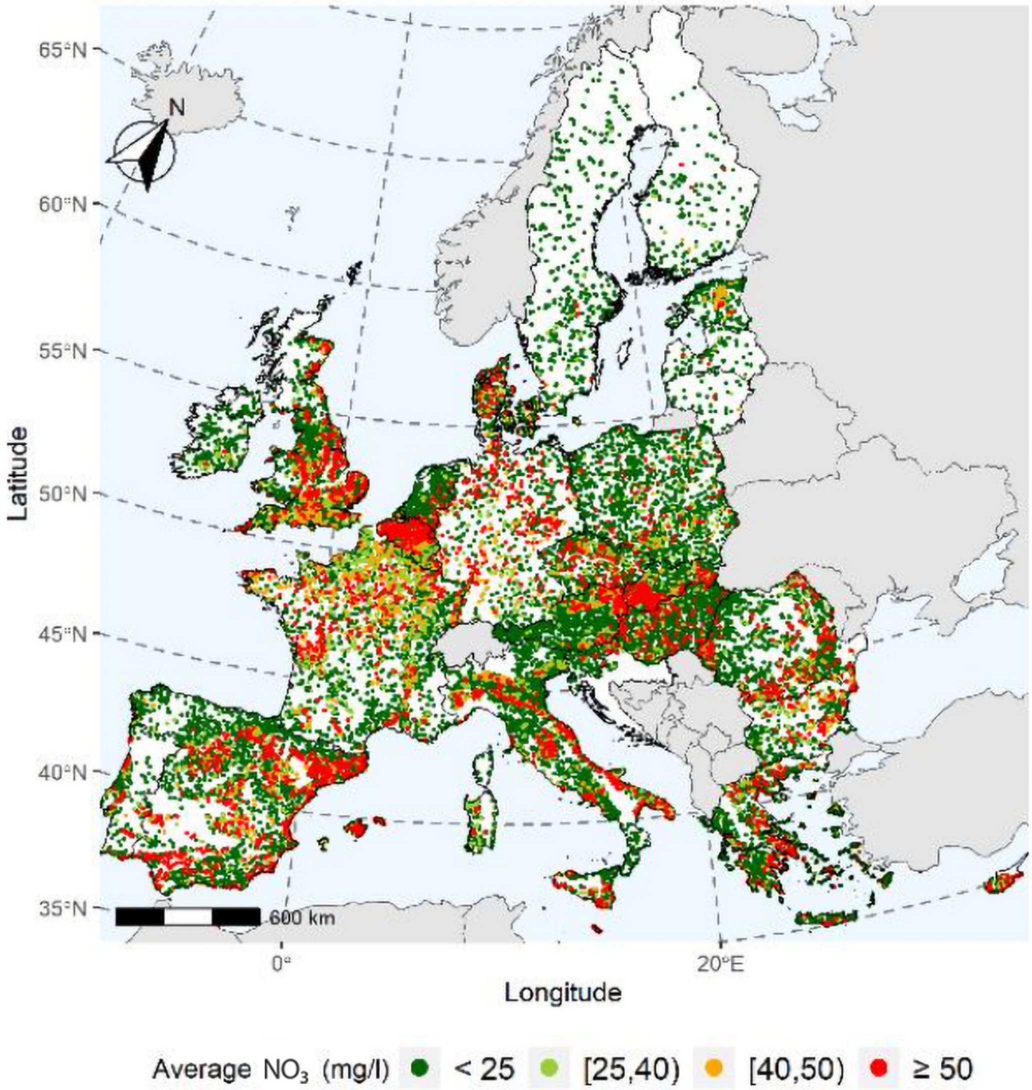

Figure 6. Annual average NO_3 concentrations in groundwater for the reporting period in EU countries. Source: [49].

The implementation of the Nitrate Directive in Ukraine has already been delayed twice in 2017 and 2018. There is still no approved methodology for determining vulnerable zones. In this context, the government should revise the timelines for implementing the Nitrate Directive in alignment with the Action Plan for the Implementation of the EU-Ukraine Association Agreement. Responsibility for this process should be assigned to the Ministry of Agrarian Policy and Food and the Ministry of Environmental Protection and Natural Resources of Ukraine, with clear designation of responsible departments and the retention of qualified personnel to ensure the continuity of this work.

The ministries should develop a Methodology for identifying areas vulnerable to NO_3 pollution and a Code of Good Agricultural Practice with further legislative regulation.

In the context of restricting pesticide use, the biological method of plant protection against pests, as an alternative to chemical treatments, is gaining strategic importance. The use of biological means increases the level of environmental safety, contributes to a radical improvement of the phytosanitary situation in agrobiocenoses, prevents contamination of agricultural products, which improves their quality and has a positive impact on human health.

According to scientists, in the coming years, it is necessary to increase the level of biologization of crop protection against pests, diseases, and weeds to 23–25% of the total rational amount of protective measures, covering 35 million hectares annually [50]. It is advisable to avoid giving subsidies from the state budget to farms that are environmentally damaged by pesticides and NO_3. Instead, support should be focused on helping farms adopt best practices of non-chemical plant protection and optimize the use of mineral fertilizers. Additional attention should be paid to technical equipment that will facilitate the greening of production.

Agriculture is a source of greenhouse gas emissions, which affects climate change [51]. The agricultural sector of Ukraine is dominated by the traditional system of soil cultivation, which is carried out with shelf-type tools [52]. This type of plowing releases ten times more soil CO_2 into the air compared to surface tillage (Figure 7).

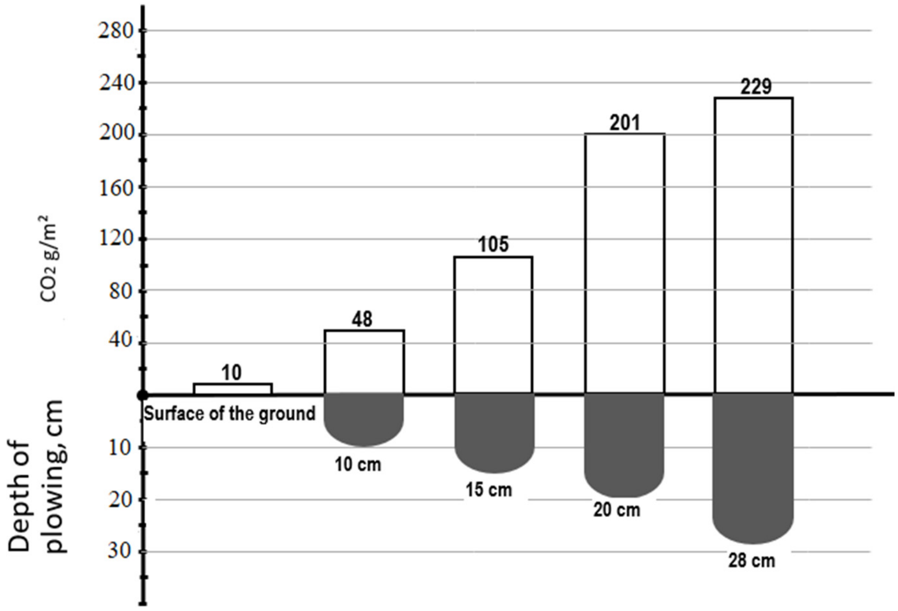

Figure 7. Total CO_2 emissions depending on the plowing depth in 24 h. Source: compiled by the author.

At the same time, agriculture is a source of N_2O emissions—58%, and CH_4—47% of total emissions [53]. According to FAO experts, by 2030, N_2O emissions will increase by 35–60% and CH_4 emissions by 60% [54].

The main sources of nitrous oxide and methane emissions are livestock and rice farming. In Ukraine, livestock farming is concentrated in small farms with land use of 1–10 hectares, where they keep 75% of livestock. There is no control over compliance with organic waste disposal rules on these farms, which is a factor in polluting not only the air but also water resources.

4. Discussion

Based on a systematic synthesis of published research on the pollution of land and other resources in the agricultural sector, we have identified the most threatening types of pollution. This study also takes into account our own observations of these processes. The identified types of pollution are particularly relevant in the current conditions of Ukraine. Understanding the negative impact of pollution on soil fertility, water resources, and product quality, and thus, on the health of consumers, is extremely important. This requires adjusting the mechanisms of state control over economic activity. It is necessary to focus on both the restoration of contaminated resources and the prevention of further development of these processes.

In relation to the conservation of land contaminated with heavy metals and radionuclides; the land areas subject to conservation in accordance with the laws and regulations are not being withdrawn. The main reason for this is the lack of mechanisms to compensate landowners and tenants for losses due to a temporary reduction in sown areas. In foreign practice, for example, in the United States, such land is transferred for conservation to a state institution with the payment of rent [55]. The same problem will arise in the post-war period, when the issue of temporary withdrawal of land affected by hostilities from cultivation will arise. Finding a consensus between the need to preserve the productivity of agricultural land through temporary conservation and supporting the economy of agricultural producers is an urgent task. This issue remains the subject of active discussions.

The transition from chemically intensified to agroecologically oriented agricultural production presents a significant and contentious challenge, particularly in identifying effective mechanisms to influence crop producers. Research suggests that the long-term competitiveness of agricultural enterprises depends on their ability to address the environmental and social impacts of their operations [56–59]. This issue is especially acute for large agro-trading and industrial companies, which dominate the Ukrainian agricultural sector but frequently resist adopting agroecological principles. This resistance underscores the need for strategic state interventions.

One effective approach is the state regulation of agricultural land distribution among business entities, which includes limiting access to land for non-agricultural companies and promoting environmentally sustainable land use [45]. Such measures not only play a critical role in preventing the establishment of an oligarchic-latifundist governance system in Ukraine's agricultural sector but also contribute to reducing pollution. By promoting responsible land management, these actions help mitigate the environmental impact of agricultural activities, enhancing soil fertility, protecting water resources, and improving overall sustainability.

Moreover, the findings and proposed solutions have broader applicability, offering valuable insights for other countries facing similar challenges of land degradation due to armed conflicts. The approaches to land conservation, ecosystem restoration, and agroecological transformation outlined in this study can serve as a model for addressing post-conflict recovery of agricultural systems worldwide, contributing to global efforts in achieving environmental and food security.

Limitations of the study: We consider it appropriate to emphasize that the recommendations and conclusions contained in this study are formed under certain limitations, of which three should be highlighted. Current research on pollution, which is analyzed in this article, is conducted in regions with the highest concentration of industry and in areas where conflicts are taking place. Due to limited access to these regions, such studies are somewhat fragmented. The full picture of the state of pollution of natural resources will be provided by research in the postwar period, which will more fully determine the ways to restore them.

Statistical and analytical data on pollution, including heavy metals, pesticides, and agrochemicals, are mostly limited to the pre-war period. This is due to the lack of information from the temporarily occupied regions, as well as the lack of access to some of the data. With this limitation removed and the spatial coverage of the study expanded, the conclusions and recommendations can be refined.

It should be noted that the ways of studying the pollution of natural resources in the agricultural sector are quite different. They are carried out by both scientific institutions and relevant international organizations and projects. This is particularly true with regard to the methods of assessing environmental impacts on agricultural production. The use of standardized approaches to determining the level of impact of different types of pollution on soil ecology could improve the quality of the results obtained. This would make them more comparable and ensure the validity of the conclusions.

These limitations point to important areas for future research on this issue. Particular attention should be paid to the development of methodological foundations for the formation of an analytical framework for making management decisions in the field of protection against critical sources of pollution. Such sources are currently the territories of the south-eastern regions affected by military operations and the Polissya regions contaminated with radionuclides.

5. Conclusions

This study assessed the most critical pollutants of natural resources in agriculture. It also analyzed their impact on land productivity, water resources, the environment, and human health.

The results show high levels of heavy metal contamination of arable land. This phenomenon is especially typical for the southeastern regions of Ukraine, where metallurgical, chemical and mining enterprises are concentrated. Currently, these regions are covered by military operations, which increase their pollution. The radionuclide contamination of the Polissia region and localized sites in other regions of the country is alarming. This contamination, caused by the explosion at the Chornobyl nuclear power plant, remains the main source of radiation hazard for the population through the ingestion of radionuclides in food. Pesticides and NO_3 are added to these sources of soil pollution. Their spread is due to the dominance of intensive chemical-oriented agriculture in the agricultural sector of Ukraine. They also act as polluters of water resources. In addition, discharges of highly mineralized mine water and polluted industrial wastewater result in massive flows of saline water into rivers, which exacerbates their negative environmental condition. Air pollutants include smoldering mining dumps, combustion products from ammunition and chemical plants damaged by explosions, and fuel as well as lubricant storage facilities in war zones. Additional sources of contamination are annual local and large-scale forest fires in areas contaminated with radionuclides.

The study confirmed that pollution of natural resources in the agricultural sector is a multifaceted problem. Its solution requires a comprehensive approach that includes policy interventions to strengthen environmental standards of management. It is also necessary to introduce technological innovations aimed at achieving a balance between economic development, environmental protection, and human health.

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