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RESEARCH ARTICLE

Monitoring and restoration of soils (agrocenoses) in the border regions of the North-Eastern Forest-Steppe of Ukraine: challenges and prospects

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Abstract

This study investigates the impact of war on soil degradation in the Sumy region and across Ukraine, highlighting risks to sustainable agriculture and evaluating strategies for restoration that align with environmental and climate resilience goals. A key challenge is the physical deterioration of soils caused by mining activities, explosions, heavy machinery movement, and chemical contamination from heavy metals and explosive residues. These war-related impacts are compounded by climate hazards such as increased drought frequency, higher erosion risks, and reduced crop quality. The findings demonstrate viable pathways for the reconstruction and recovery of the agricultural sector in the Sumy region. Proposed measures include bioremediation technologies, the use of green manures, agroforestry, land-use zoning, and the development of precision farming. Furthermore, certain crop varieties and hybrids-including cereals (wheat, barley, corn), oilseeds (sunflower, rapeseed), and legumes (soybeans) were identified as having the ability to either minimally accumulate pollutants in edible grains or concentrate them in non-edible parts, ensuring both safe consumption and compliance with export standards to the EU. The article describes in detail the problems of the impact of war on the environment and the implications for a sustainable transition, drawing on data from primary literary sources and reports.

Keywords: Mycorrhizae, Food phytoresources, Inoculation, Soil biota, Seed treatment, Yield, Phytocenoses, Soil fertility, Soil structure, Expertise

Introduction

The border zone conflict in the Sumy region caused severe damage to arable lands, which have long been the foundation of the local agricultural sector. Ongoing fighting, shelling, and the movement of heavy equipment have caused physical damage to soils: Craters formed, the structure of the arable layer was destroyed, and erosion intensified (Ecoaction, 2024). Contamination from explosives, heavy metals, lubricants, and other toxic substances poses an additional threat to soil fertility and agricultural product safety (Prysedzka and Shramovych, 2023). Large areas in the border region are mined, making their use unsafe until demining operations are carried out (Kostenko and Honcharova, 2024). Mechanical stress further compacts the soil, reducing permeability and increasing erosion risks. Hostilities during this period negatively affected soil biota, leading to a reduction in both the abundance and diversity of essential microorganisms critical for soil fertility.

These processes are further aggravated by climate change, including disruptions in hydrological balance, rising temperatures, and shifts in precipitation patterns (FAO, 2022). Our research examines the war-induced degradation of soils in the Sumy region, identifies threats to sustainable agriculture, and explores rehabilitation strategies that incorporate environmental and climate sustainability considerations. The implementation of comprehensive measures for soil protection and restoration, as well as systematic monitoring of their condition using modern technologies, is recommended.

Materials and Methods

During the preparation of this paper, we employed theoretical methods of analysis, including a review of literature sources and agricultural practices reported on farmers' websites; synthesis to construct illustrations and categorize results; and induction and deduction to formulate scientific positions, research tasks, and conclusions with recommendations. The socio-specific method was also applied in the context of implementing educational practices related to farming, as well as within the private agricultural sector. The scientific contributions presented in this paper include the classification of agrotechnological practices for sustainable farming in the border areas of the Sumy region, along with the development of key recommendations emphasizing the importance of farmer training in these areas.

Results and Discussion

One of the most pronounced consequences of the war on agricultural land in the border areas of the Sumy region is physical soil degradation. Cratering from artillery shelling destroys the fertile layer, compromising its capacity to retain water and nutrients (Solokha, et al. 2023, 2024). Unexploded ordnance poses an additional threat, with approximately 30% of cultivated land requiring demining. This renders the soil unsuitable for cultivation, leading to abandonment. The use of heavy machinery compacts the soil, restricting water infiltration, reducing porosity and oxygen availability to plant roots, thereby decreasing fertility and increasing erosion risks (Kostenko and Honcharova, 2024). Restoration measures are required, including soil loosening, filling craters with fertile substrate, and applying bioremediation techniques.

War results in chemical soil pollution in the border areas of the Sumy region. Toxic substances infiltrate the ground, including explosive residues, heavy metals, and combustion products from equipment (Datsko, et al. 2024, 2025). TNT and hexogen explosives disrupt the acid-base balance and produce toxic compounds that can penetrate plant tissues. Heavy metals, including lead, cadmium, mercury, and copper, are yet another source of contamination, originating from ammunition and equipment. Even after the cessation of hostilities, such soils are dangerous without special cleaning. All the above-mentioned soil disturbances repress soil microflora, disrupt biochemical transformations and reduce bioproductivity. Pollution will persist for tens of years, rendering the land unusable for agriculture without the use of specialised purification methods.

Government reports by the Ministry of Ecology and Natural Resources of Ukraine document enormous land destruction in the Sumy Oblast. To date, as of 2023, more than 40% of the arable lands of the Sumy region border land require demining and restoration activities for fertility (Ministry of Ecology, 2023). This is because physical destruction of the land, as well as chemical contamination resulting from explosions and the use of toxic substances, has occurred.

Climate change significantly affects the condition of Sumy region soils, particularly due to droughts and altered precipitation regimes. The decrease in precipitation and its unevenness disrupts the water balance of soils, making them less fertile (IPCC, 2024). Intensive rains that fall within a short period cause erosion, as water does not have time to be absorbed, thereby stripping away the fertile layer and nutrients. Regular droughts result in soil drying, a reduction in organic matter, and compaction, which make restoration challenging. Wind drives off the highest, fertile layer, wasting organic content and nutrients that are crucial for plant life. The clearing of forest belts and other windbreaks leaves the land vulnerable to erosion processes, enhancing the degradation of the farmland.

In agricultural fields where physical, chemical, and biological soil characteristics have undergone significant changes due to the war, producing ordinary crops becomes extremely challenging. For example, erosion, heavy metal pollution and mining can alter soil pH, water regimes, and nutrient content, making ordinary crops less apt. Ongoing drought and temperature fluctuations further complicate farming. New varieties that resist stress and incorporate renewal farming practices, such as organic farming and soil enhancement technologies, therefore need to be developed.

Arable land restoration options

The best method of reclaiming agricultural land after a war is through the use of green manure and agroforestry. They improve soil structure, incorporate organic matter into the soil, and control the water regime, which is essential for sustainable agriculture.

Green manures are crops that are grown to fertilize the soil. They replenish it with nitrogen, improve its composition, increase the level of humus and inhibit pathogens, which is especially important after explosive or toxic contamination (Scavo, 2022). Some of the most suitable green manures that can reduce acidity and improve the soil fertility are lupine, mustard, rapeseed and butternut squash.

Agroforestry refers to the use of trees (poplar, acacia) for stabilizing soils and eradicating erosion in eroded or mined land. Agroforestry refers to the use of forest cover for the recovery of eroded land, particularly in areas prone to erosion or those affected by hostilities (Plieninger, et al. 2020).

Agrotechnical practices play a significant role in restoration. Practices are the application of organic and mineral fertilizers (manure, compost, NPK), adjustment of acidity (liming), deep loosening, ploughing and mulching. Practices improve the chemical and physical properties of the soil, enhancing its water-holding capacity and aeration (UNCCD, 2021). Mulch, cover crops, or irrigation are used to conserve moisture for climate change mitigation purposes. Agrotechnical measures are cost-effective and inexpensive and can be used in conjunction with other forms of restoration, such as bioremediation and agroforestry. We compiled a list of the primary agrotechnological methods for soil restoration (Fig. 1).

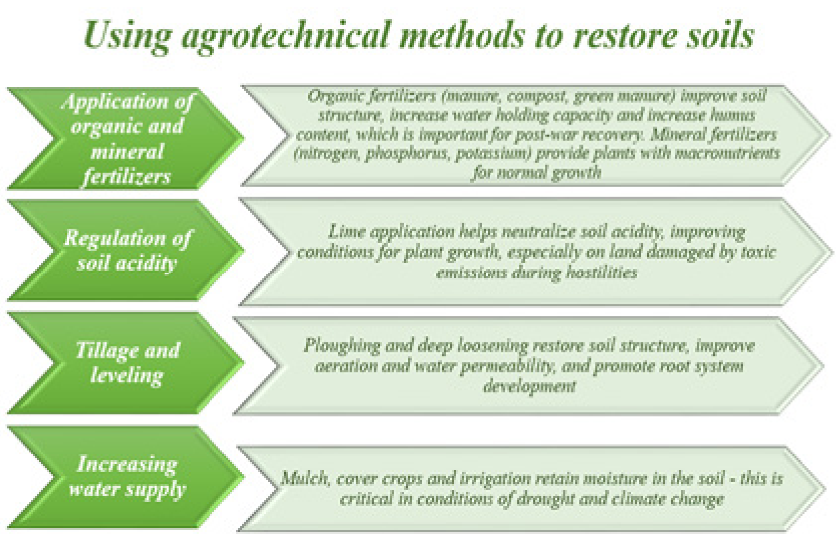

Figure 1. List of the primary agrotechnological methods for soil restoration.

Strategic solutions for sustainable agriculture in border regions

For the Sumy region border zones, where military operations have led to severe soil damage, zoning is the key method for restoring agricultural production and sustainable land use. The first task of zoning is to assess high-potential lands for rehabilitation and crop development. This entails analysing the physical, chemical, and biological characteristics of soils, such as their fertility, structure, water-holding capacity, and level of contamination. For these lands, it is necessary to implement measures to enhance their quality, such as introducing organic and mineral fertilisers, green manure, and improving drainage and water supply. Definition of these territories will allow agricultural output optimization of existing resources and maximization of productivity without overloading the soil.

Another key factor in zoning is the location of zones that will require long-term conservation following the war to prevent further damage. They include areas that undergo intensive mechanical devastation as a result of war, such as those affected by mining or processing using heavy machinery, and land extensively contaminated with chemicals due to explosive residue or heavy metals. These soils require a recovery period that can extend for several years. In these situations, conservation practices such as planting cover crops, agroforestry, or establishing nature reserves can be implemented, which will enable soils to regenerate without any additional anthropogenic activity.

Precision Farming Technologies (PFTs) represent a novel agricultural production technology that can significantly increase resource efficiency, reduce expenses, and mitigate adverse environmental effects (European Commission, 2020). During the post-war reconstruction of Sumy Oblast's border areas, where soils have become impoverished due to military activities, the adoption of these technologies is an imperative measure for restoring fertility and advancing sustainable agricultural development (Zakharchenko, et al. 2024). Precision farming technologies will reduce the human factor, increase the efficiency of resource use, and help preserve natural ecosystems on territories affected by the war (FAO, 2021). We grouped the data and results from the literature mentioned above in a diagram that illustrates the implementation of precision farming technologies (Fig. 2).

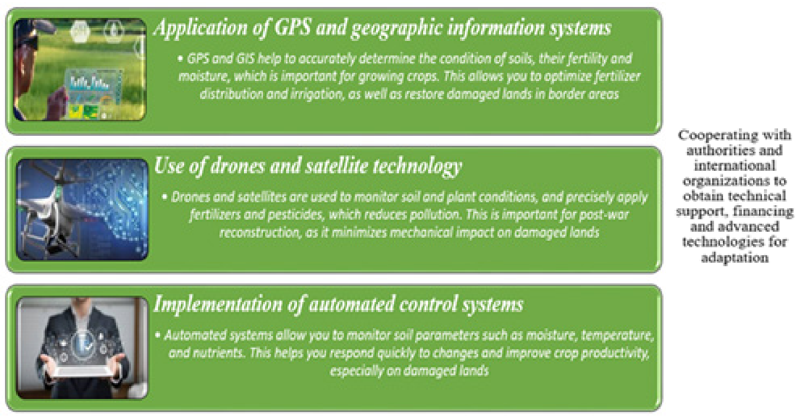

Figure 2. Implementation of precision farming technologies for soil restoration and improving crop production.

One of the most significant prerequisites for sustainable agricultural development within the context of climate change is the practical training of agrarians and farmers in adaptive practices that reduce the negative impact of climate change on their farms. The agricultural producers face new challenges resulting from soil degradation, changes in precipitation and drought regimes, as well as degradation threats, educational initiatives are becoming a strategic means of increasing the sustainability and productivity of agricultural production. We created a diagram that illustrates the implementation of educational practices by farmers on problem arable land (Fig. 3). The role of training in addressing problems and improving agricultural product quality is mentioned in publications of authors from the EU (UNFCCC, 2020, UNDP, 2020).

Figure 3. Implementation of precision farming technologies for soil restoration and improving crop production.

Collaboration with global environmental initiatives is a key element of the rehabilitation strategy for fertile lands in border territories, particularly the Sumy region, following war destruction (Fig. 4). Global environmental initiatives can provide the technical, financial, and expert assistance necessary for introducing new and sustainable agricultural technologies, one of the most significant elements in restoring damaged lands, as well as adapting to climate change.

Figure 4. The role of international support in the restoration of arable lands in the Sumy region.

Note for Ukrainian exporters of agricultural products to EU countries

EU countries have established standards for farm product exporters regarding the maximum permissible levels of pollutants in agricultural products (WHO, 2021). Particular attention should be paid to controlling the content of: Cadmium, because it is the most toxic metal and strict standards have been established for grain products. Even small concentrations can be dangerous for humans; Lead-excessive amounts can affect the human nervous system; Mercury-has high neurotoxicity; Arsenic-excessive amounts of its compounds provoke diseases of the nervous system, skin, and brain.

Given the high intensity of hostilities in Ukraine, importing countries may need to conduct additional analysis for specific elements, such as nickel and chromium, which can also pose health risks to the human body. Copper and zinc are essential trace elements for plants, but their excess indicates potential contamination. Analysis of the content of antimony and other components can be introduced as part of expanded measures to control the quality of soils and agricultural products.

We have compiled a list of the main crops that, according to the literature, tend to accumulate fewer heavy metals, such as cadmium, lead, mercury, and arsenic, in their vegetative parts or can be used in complex phytoremediation measures (Kumar, et al. 2021, UNCCD, 2021, Uridia, et al. 2021, UNEP, 2021).

Cereals: Wheat (*Triticum aestivum*). Some varieties possess the property of limiting the transfer of cadmium and other metals into the grain, making this crop popular for cultivation in fields with low levels of contamination. Barley (Hordeum vulgare), like wheat, often has a lower capacity to accumulate heavy metals in the grain, reducing the risk to consumers. Corn (*Zea mays*). Some varieties of corn exhibit a less active transfer of metals into the grain, allowing this crop to be used even in the presence of certain levels of soil contamination.

Oilseeds: Sunflower (*Helianthus annuus*). Due to its ability to accumulate heavy metals in the root system, this crop acts as a "soil cleaner". At the same time, the seed part can remain relatively clean, provided it is appropriately managed. Rapeseed (*Brassica napus*). An oilseed crop that, under certain conditions, demonstrates a lower level of heavy metal translocation into edible parts. It can be used in crop rotations where crops are changed properly (not monoculture) or alongside crops that contribute to reducing metal bioavailability.

Legumes: Soybeans (*Glycine max*). Although heavy metal accumulation in soybeans may depend on variety and soil conditions, some studies show that certain varieties have a lower capacity to accumulate metals in the beans, which is essential for consumer safety.

Careful selection of varieties and regular soil analysis will help minimize the risk of metals in food products. Even though a specific crop is selected, it is important to use agrotechnical methods to reduce the bioavailability of heavy metals, such as applying lime to neutralize soil acidity or gypsum to neutralize alkalinity, applying organic fertilizers, compost, humates, biochar, and the proper irrigation to correct the irrigation regime.

Conclusion

For sustainable agriculture in border areas, an integrated approach is proposed, combining soil restoration, climate change adaptation, and the adoption of sustainable agricultural technologies. Direct assistance through training programs, financing of environmental initiatives, and technology transfer is essential for achieving long-term results. It has been determined that certain crop varieties and hybrids-such as cereals (wheat, barley, corn), oilseeds (sunflower, rapeseed), and legumes (soybeans)-minimally accumulate pollutants in grains or concentrate them in inedible parts, thereby ensuring their safe consumption and eligibility for export to the EU. The recovery of productive lands in the border areas of Sumy oblast is not only a responsibility of farmers but also a critical component of Ukraine's environmental security strategy, community revival, and sustainable future. Soil improvement cannot be achieved without its support and the application of sustainable agricultural methods through international cooperation with the implementation of joint projects and grants, as well as the integration of international environmental policies, especially those of European countries. At the same time, sustainable agriculture helps to reduce the negative impact on the climate.

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