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SOIL DAMAGE AND RECOVERY IN UKRAINE: LESSONS FROM GLOBAL POST-WAR EXPERIENCES

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Abstract. *The russian invasion of Ukraine has resulted in extensive environmental damage, significantly affecting the country's soil quality and raising concerns about long-term agricultural sustainability and environmental health. The war has resulted in soil degradation through contamination by military operations, destruction of farmland, and disruption of natural ecosystems. The objective of the research is to evaluate the environmental consequences of the war in Ukraine, with a particular emphasis on soil degradation and the development of strategies for post-war restoration. The manuscript will entail a comprehensive review of existing literature on soil degradation and post-war environmental restoration, with a particular focus on case studies from conflict zones such as Vietnam, the Balkans, and post-Second World War Europe. Furthermore, an analysis of data from Ukrainian government agencies, environmental organisations, and international bodies will be conducted to assess the extent and nature of soil damage caused by the war. To achieve effective recovery of its soils and ecosystems, Ukraine can draw on global experiences and implement long-term strategies combining modern decontamination technologies, sustainable agricultural practices and policy reforms that promote ecological resilience. It is imperative that environmental, social, and economic factors be integrated into the country's post-war recovery strategy. It is imperative that international cooperation and investment in environmental restoration, in conjunction with community involvement, are pursued in order to guarantee the success of these endeavours and to provide Ukraine with the support it requires in order to achieve a sustainable and resilient agricultural future. The research provides a foundation for the development of integrated strategies that leverage global lessons, thereby ensuring long-term recovery for Ukraine's soil and agricultural systems.*

Keywords: *agriculture, pollution, soil damage, erosion, heavy metal, oil spill, landmine*

Relevance of the research. Soil pollution represents a significant environmental issue with global repercussions, frequently resulting from industrial, agricultural, and urban activities. However, one lesser-known yet impactful source of soil pollution arises from war and military conflicts. The deployment of hazardous substances, such as explosives, chemicals, heavy metals, and oil spills, during warfare inevitably results in soil contamination. The destruction of ecosystems during armed conflicts often leads to long-term degradation of arable land, thereby impeding post-war recovery for affected populations and the country in general [24].

As the global economy was beginning to recuperate from the effects of the pandemic, a new crisis emerged with the invasion of Ukraine by russia, resulting in a war in Europe [41]. The russian invasion of Ukraine which intensified in February 2022 precipitated the most significant armed conflict in Europe since the Second World War. The consequences of this situation have not been confined to the countries directly affected; they have also had an impact on Europe and the broader global community indirectly, through the issue of food security [11, 17].

In addition to the human toll, the conflict has resulted in considerable environmental damage, with a particular impact on Ukraine's soil, agricultural sector, and ecosystems [23]. The war has served to exacerbate the pre-existing environmental challenges, while simultaneously introducing novel and acute risks associated with military operations.

Analysis of the latest research and publications. The profound impact of war on human lives is well documented. However, the natural environment, which encompasses soil, water, air, and living organisms, is frequently overlooked amidst the devastation. This is despite the fact that human lives are inextricably linked to the natural environment.

The latest research and publications on the environmental impact of armed conflicts have revealed the extensive damage inflicted by war on ecosystems, with soil degradation evoking significant concern [19, 35]. The war has caused extensive environmental destruction and soil contamination in Ukraine. Of particular concern is the damage to the country's fertile agricultural soils, which constitute a critical component of its economy. Ukraine is renowned as the "breadbasket of Europe", with its expansive tracts of fertile black soil (Chernozem) ranking among the most productive in the world [23].

Ukrainian and international environmental agencies and research organizations have commenced the documentation of the effects of the war on the country's natural resources [4, 17, 26]. These include soil contamination from heavy metals and fuel residues, erosion from disturbances on the battlefield, and the disruption of agricultural systems.

It has been demonstrated that military operations, including the utilisation of explosives, the transportation of heavy machinery, and the contamination of the environment with chemical substances, have a considerable impact on the structure of the soil, the composition of nutrients, and biodiversity [16].

Global case studies on post-conflict soil restoration, including those from post-Second World War in Europe offer valuable insights into the rehabilitation of conflict-affected soils [28]. Furthermore, recent publications have examined the role of sustainable agricultural practices in post-conflict recovery as the efficacy of terracing, crop diversification, and organic farming in restoring soil health and ensuring food security in the aftermath of war. Research also underscores the importance of involving local communities and stakeholders in the recovery process, a lesson that Ukraine could benefit from in its restoration efforts [12].

The purpose of this research is to examine the environmental impacts of the war in Ukraine, with a particular emphasis on soil quality, and to investigate potential strategies for post-war soil restoration. By analysing global experiences in post-conflict soil recovery, the research aims to provide insights and recommendations for restoring Ukraine's damaged landscapes, ensuring sustainable land use, and supporting long-term ecological resilience.

Methods and objects of the research. A review of the existing literature on the subject based on cited publications will be conducted. A comprehensive review of existing literature on soil degradation and post-war environmental restoration will be conducted, with a particular focus on case studies from conflict zones such as Vietnam, the Balkans, and post-Second World War Europe.

The data will then be subjected to analysis. An examination of data collected from Ukrainian government agencies, environmental organisations and international bodies will be conducted to determine the extent and types of soil damage resulting from the war.

Research results and discussion. As of September 2024, the Ministry of Environmental Protection and Natural Resources of Ukraine [26] has estimated the financial and environmental impact of military actions to be UAH 2.596 trillion. This figure was calculated by the State Environmental Inspection in accordance with the approved methodology and represents the estimated damage resulting from the aforementioned actions. A total of 5,909 cases of environmental damage resulting from the armed aggression of russian federation have been recorded and documented.

In terms of land resources, the estimated financial loss is UAH 1.15 trillion, based on 2,912 documented cases of damage. The total area of land affected by littering is more than 19.8 million m^2, while the contaminated soil area is estimated at more than 945,140 m^2, with an estimated financial loss of more than UAH 18.25 billion.

In the context of an ongoing armed conflict in part of Ukraine, soil contamination with lead and fluoride has been identified as a significant environmental concern, warranting further investigation. For instance, in Dnipro region, the concentration of lead has been found to exceed the maximum permissible concentration (MPC) by three times, while in Mykolaiv, the concentration of lead has been found to exceed the MPC by five. The concentration of zinc, copper, fluoride, and oil products has decreased by a quarter; in Zaporizhzhia region, the concentration of lead has increased by 11.17 times the MPC, the concentration of zinc and fluoride has increased by half, the concentration of petroleum products has increased by 35 %, and the concentration of phosphates has increased by 30 % [9].

At this stage, the analysis is limited to a broad overview of the conflict and its consequences. Subsequently, the focus will shift to the immediate and long-term challenges Ukraine is confronted with in its recovery process. This will include an examination of the necessity for environmentally conscious strategies to address the multitude of environmental issues that have been exacerbated by the war.

A substantial body of research has demonstrated the significant and enduring impact of armed conflict on soil quality and ecological systems. The environmental consequences of warfare are manifold and context-specific. Nevertheless, a number of pivotal findings have emerged from studies examining the impact of warfare on soil, including the following: heavy metal contamination, erosion and land degradation, oil and fuel spills, unexploded ordnance and landmines.

Heavy metal contamination. Research has demonstrated that war can result in significant heavy metal contamination of soils in conflict zones, for instance, Iraq, Syria [25], and the Balkans [34]. Elevated concentrations of metals such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and depleted uranium (DU) have been identified in soils affected by military action. These metals originate from munitions, military vehicles, and destroyed infrastructure.

Soil samples from conflict zones in Iraq [1] exhibited elevated concentrations of lead and cadmium, exceeding the threshold levels deemed safe for agricultural and residential use.

The utilisation of depleted uranium (DU) munitions in military conflicts, such as the Gulf War, has resulted in the residual presence of radioactive materials in soil, which presents long-term risks to ecosystems and human health [15].

The impact of heavy metal contamination on soil fertility can be considered to have twofold consequences: firstly, it renders land unsuitable for agricultural use, and secondly, it poses a risk to the food chain and water supplies.

The phytoremediation method makes use of plants to absorb, accumulate and detoxify heavy metals from soil. Specific plant species, designated as hyperaccumulators, have the capacity to concentrate metals such as lead, cadmium, and arsenic within their tissues. Subsequently, the plants are harvested and safely disposed of. Notable examples include sunflowers and Indian mustard, which have demonstrated efficacy in soil detoxification in contaminated war zones such as Iraq [14].

Bioremediation employs the use of microbial organisms to facilitate the degradation of contaminants or the transformation of these substances into less harmful compounds. Specific bacteria and fungi are capable of metabolising heavy metals or reducing their mobility in the soil. For example, the use of Pseudomonas bacteria has been demonstrated in post-conflict regions as a means of addressing lead and cadmium pollution [8].

The replanting of trees and the implementation of erosion control measures serve to stabilise the soil, thereby reducing the potential for the spread of contaminants through wind or water runoff. Furthermore, trees and vegetation can assist in the sequestration of heavy metals, thereby preventing their entry into the broader ecosystem [7].

Soil washing is a process whereby the contaminated soil particles are physically separated through the use of water or chemical solutions. This method has the potential to reduce metal concentrations to safer levels and has been employed in regions that have been heavily polluted by conflict, including Kosovo and Serbia [13].

An alternative approach involves the addition of chemical agents, such as lime, phosphate, or biochar, to the soil. These agents bind heavy metals, preventing their absorption by plants or leaching into groundwater. The stabilisers immobilise the metals, reducing their bioavailability. This technique is frequently employed in regions affected by industrial and military contamination [7].

Erosion and land degradation. It has been demonstrated that military activities disrupt the physical, chemical, and biological properties of soil, leading to significant degradation [8, 18]. For example, the movement of heavily tracked military vehicles has been observed to increase soil compaction [32], while disturbances caused by tanks have been shown to negatively affect soil quality, resulting in harm to invertebrate populations and vegetation [3].

The research of Almohamad [2] was to identify the characteristics and variations of soil erosion in the context of armed conflicts in the Northern Al-Kabeer River basin in Syria. The mean soil erosion rate is 4 t ha^{-1} per year, with a standard deviation of 6.4 t ha^{-1} per year. Approximately 10.1 % of the basin is subject to a tolerable soil erosion rate, while 79.9 % of the study area has experienced erosion at varying degrees. In areas affected by armed conflict, forest fires tend to result in the dominance of land cover types such as coniferous forest, transitional woodland, and scrub on steeper slopes. In the upper part of the basin, these land cover types exhibited average post-fire soil loss rates that were 200 % to 800 % higher than in the pre-fire situation.

It is frequently the case that military conflicts result in the destruction of forests and other forms of natural vegetation, which in turn gives rise to severe soil erosion. The use of bombs, artillery shelling, and chemical defoliants during conflicts has been documented as a cause of widespread deforestation in research conducted in Afghanistan and Vietnam. In Afghanistan [36], soil erosion has increased significantly in areas that were subjected to intensive bombing during decades of conflict. This has resulted in the desertification of former agricultural land, thereby rendering recovery more challenging.

In Vietnam [37], researchers observed that extensive deforested areas, particularly those treated with herbicides, continue to experience difficulties in regenerating, which has led to soil degradation and a reduction in agricultural productivity.

Furthermore, combat-related activities have been demonstrated to result in a reduction of essential soil components, including total carbon (C), nitrogen (N), microbial biomass, and soil respiration rates [10]. The flux of soil carbon dioxide (CO_2) is particularly susceptible to the level of disturbance [33], thereby underscoring the impact of military actions on soil health. Even foot traffic during military training exercises has been demonstrated to compact the soil, decrease water infiltration rates, reduce above-ground biomass, and exacerbate soil erosion [40].

On-site observations at Ar. the Rimam depression of the Sabah Al-Ahmad Nature Reserve in Kuwait [30] demonstrated that the damage to this site was caused by three primary factors: munition disposal pits (11,3 % of the area), compacted areas between pits (36,4 %), and compacted road tracks (3,6 %). The results of the field investigations of soil profiles and laboratory characterisation of soil samples indicated a significant disruption of pedogenic processes, a loss of topsoil, severe soil compaction, a reduction in the infiltration rate, contamination with munition materials, and alterations in chemical properties. Despite the presence of higher vegetation cover in the pits compared to the adjacent compacted areas, the percentage of vegetation cover was found to be significantly lower than that observed during the pre-disturbance period. The soil and vegetation assessment also indicated that the natural recovery process did not fully restore the land and vegetation to their pre-disturbance status.

For example, research from Vietnam highlights the significance of extensive reforestation and the utilisation of bioremediation techniques to detoxify soils contaminated by chemical agents [29]. Similarly, studies from the Balkans emphasise the critical role of erosion control measures and landscape restoration in preventing further environmental degradation [7].

The impact of erosion is the stripping away of the fertile topsoil that is necessary for plant growth, which has the effect of severely reducing agricultural potential and exacerbating food insecurity in post-war areas.

Oil and fuel spills. In numerous contemporary armed conflicts, military vehicles, tanks, and aircraft have been identified as a significant source of environmental degradation, largely due to fuel and oil spills. The contamination of soil by hydrocarbons, heavy metals, and toxic chemicals resulting from such spills has been demonstrated to cause long-term damage to biodiversity, agricultural productivity, and water resources. For instance, during the Gulf War, extensive oil spills and the destruction of oil wells resulted in the release of considerable quantities of petroleum into the soil [15]. The soil in Kuwait was significantly contaminated by oil spills and soot from burning oil wells, which resulted in notable alterations to the soil's physical and chemical properties. The contamination of soil with petroleum has resulted in a reduction in soil fertility and the introduction of toxic hydrocarbons, which persist in the environment and are challenging to remediate [27].

The contamination of soil with petroleum disrupts the chemical composition of the soil, kills vegetation, and renders the land unsuitable for agricultural or natural regeneration. For instance, the rate of biodegradation of oil products for different levels of pollution in Chernozem was determined over a period of 24 months [22]. The content of hydrocarbons decreased by 85–87 % and 60–64 %, respectively. One of the key mechanisms for the loss of hydrocarbons from the soil surface is microbiological decomposition. Studies have demonstrated that in the oil concentration range of 6,4–24,6 l/m², there was a notable increase in the intensity of carbon dioxide release from the soil, which is 60 % higher than in the control option. This indicates an intensification of the processes of its biodegradation. The impact of soil pollution with oil on diagnostic indicators such as soil pH and the content of water-soluble potassium and sodium was found to be less significant than the influence of the time factor. The phytotoxicity of oil-contaminated soil was also demonstrated to have a negative impact on seed germination in field conditions. The research results indicate a gradual self-purification of the soil from petroleum hydrocarbons during the observation period.

A variety of methods, including physical, chemical, and biological, are available for addressing oil spills. The initial two methods are constrained by factors such as elevated costs, inefficacy, and disruption to the natural ecosystem [39]. As an alternative, bioremediation offers an environmentally friendly process for the removal or reduction of petroleum pollutants in the environment through the use of selective microbial flora [31].

Baniasadi & Mousavi [5] proposed that bioremediation represents a more environmentally friendly approach than physicochemical methods, which are more cost-effective and cause less disruption to the environment.

In 1991, Kuwait oil fires resulted in the combustion of numerous oil wells, leading to the release of millions of barrels of oil into the surrounding desert environment. This incident caused significant contamination of the soil. Large-scale bioremediation and soil washing efforts were undertaken with the objective of restoring the land. The Iraq conflict (post-2003) resulted in substantial damage to oil infrastructure, with spills contaminating both land and water. Bioremediation was employed as a means of cleansing soil that had been rendered polluted by oil and fuel spills. In this method, natural or genetically modified microorganisms are applied to the polluted site, and/or the polluted environment is enriched with nutrients. These processes are known as bioaugmentation and biostimulation, respectively. The primary focus of attention is due to the fact that these methods have been the subject of scientific investigation by the research community with regard to their potential for the treatment of oil spills, primarily at the laboratory scale, with less extensive investigation in real-world settings.

Unexploded ordnance (UXO) and landmines. The presence of unexploded ordnance and landmines in the aftermath of armed conflicts continues to present a significant risk to soil quality and land use. The presence of UXO can result in soil contamination with explosive residues and heavy metals.

The results of studies conducted in Cambodia [21] and Bosnia [20] indicate that soils contaminated with explosive residues have undergone alterations in microbial communities and have exhibited disrupted plant growth. The presence of UXO precludes the safe utilisation of land for agricultural and developmental purposes, resulting in the underutilisation of vast tracts of arable land due to concerns regarding potential detonation.

The impact of UXO on the environment can be significant. The presence of UXO and landmines impedes the post-war recovery and development of agricultural activities. Furthermore, the detonation of ordnance results in the release of toxic chemicals into the soil, thereby exacerbating the pollution.

The identification of unexploded ordnance and landmines can only be addressed through the utilisation of a stochastic-deterministic model but the eventual creation of risk-hazard maps requires preliminary work involving laboratory experiments and field surveys. Baselt et al [6] put forward a novel approach to the problem within the context of an international research project. The objective is to produce risk-hazard maps that can be employed by elected decision-makers, administrative authorities, and emergency personnel in affected municipalities.

Unpiloted aerial systems featuring advanced remote sensing capabilities represent a significant technological advancement with the potential to significantly impact the resolution of the explosive ordnance crisis. In particular, recent developments in hardware engineering have facilitated the effective deployment of compact, lightweight, and less power-consuming hyperspectral imaging (HSI) systems from small unpiloted aerial vehicles (UAVs). The results demonstrate that the analysis of hyperspectral imaging (HSI) data sets can yield spectral profiles and derivative data products, which are capable of distinguishing between multiple ERW and mine types in a range of host environments [38].

Conclusions. The research on war-affected soils has revealed the significant environmental degradation that follows military conflicts, particularly in relation to heavy metal contamination and soil erosion. These issues can impede recovery for decades. The implementation of remediation strategies necessitates the formulation of long-term plans, encompassing the utilisation of contemporary decontamination technologies, the adoption of sustainable land use practices, and the allocation of substantial financial resources to facilitate the restoration of ecosystems and to bolster agricultural and economic recovery in post-conflict societies.

The United Nations Environment Programme (UNEP) has highlighted the necessity for integrated strategies that address both environmental and social concerns, advocating for policy frameworks that ensure sustainable land management and ecological recovery. The research emphasises the importance of considering environmental, social, and economic factors in soil restoration, offering insights that can inform the recovery process in Ukraine, drawing on global examples of successful post-war remediation strategies.

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ПОШКОДЖЕННЯ ТА ВІДНОВЛЕННЯ ҐРУНТІВ В УКРАЇНІ: УРОКИ СВІТОВОГО ПОВОЄННОГО ДОСВІДУ

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Анотація. *Російське вторгнення в Україну призвело до значної шкоди навколишньому середовищу, суттєво вплинувши на якість ґрунтів країни та викликавши занепокоєння щодо довгострокової стійкості сільського господарства та здоров'я довкілля. Війна призвела до деградації ґрунтів через забруднення внаслідок військових дій, знищення сільськогосподарських угідь та порушення природних екосистем. Метою дослідження є оцінка екологічних наслідків війни в Україні, з особливим акцентом на деградацію ґрунтів та розробку стратегій післявоєнного відновлення. Рукопис передбачає всебічний огляд існуючої літератури з питань деградації ґрунтів та повоєнного відновлення довкілля, з особливим акцентом на тематичних дослідженнях із зон конфліктів, таких як В'єтнам, Балкани та Європа після Другої світової війни. Крім того, буде проведено аналіз даних українських урядових установ, екологічних організацій та міжнародних організацій для оцінки масштабів і характеру ґрунтових пошкоджень, спричиненних війною. Щоб досягти ефективного відновлення ґрунтів та екосистем, Україна може використати світовий досвід і впровадити довгострокові стратегії, що поєднують сучасні технології знезараження, стійкі сільськогосподарські практики та політичні реформи, які сприяють екологічній стійкості. Вкрай важливо, щоб екологічні, соціальні та економічні фактори були інтегровані в стратегію післявоєнного відновлення країни. Міжнародне співробітництво та інвестиції у відновлення довкілля у поєднанні із залученням громадськості є запорукою успіху цих зусиль та надання Україні підтримки, необхідної для досягнення сталого та життєздатного сільськогосподарського майбутнього. Дослідження створює основу для розробки комплексних стратегій, які враховують глобальний досвід, забезпечуючи тим самим довгострокове відновлення ґрунтів та сільськогосподарських систем України.*

Ключові слова: *сільське господарство, забруднення, пошкодження ґрунтів, ерозія, важкі метали, розлив нафти, наземні міни*