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SOIL DEGRADATION IN THE CONTEXT OF ARMED CONFLICT: A CONCEPTUAL FRAMEWORK

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The large-scale military invasion of Ukraine has triggered an environmental crisis, dramatically intensifying pre-existing processes of soil degradation and introducing new threats to soil health, ecosystem function, and national food security. This review is highly relevant given the unprecedented scale of military disturbance, the diversity of affected landscapes, and the far-reaching impacts on agricultural production and ecological stability. The purpose of this work is to comprehensively synthesize current Ukrainian and international research on the impacts of military activities on soils, focusing on the mechanisms and feedbacks underlying war-related degradation. Methods include systematic literature analysis, integration of field and remote sensing data, and case study evaluation. The review analyzes four key dimensions of soil system change: physical disturbance (compaction, erosion, cratering), chemical contamination (heavy metals, explosives, oil products), biological decline (loss of microbial and plant diversity), and social disruption (land abandonment, reduced productivity, risks to livelihoods). The results show that warfare accelerates soil degradation through multiple interacting pathways, leading to cumulative impacts and the risk of ecological "regime shifts," where soils lose resilience and recovery potential. Scientific novelty is provided by an integrated conceptual framework that explicitly connects physical, chemical, biological, and social feedbacks, drawing on both Ukrainian and international evidence. The practical significance lies in identifying major knowledge gaps and highlighting the urgent need for interdisciplinary, systems-based monitoring and adaptive management. The model and recommendations are applicable not only to Ukraine, but to all regions facing environmental impacts of armed conflict, and can inform evidence-based policy and restoration strategies.

Key words: *soil health, ecosystem resilience, land degradation, military disturbance, chemical contamination, remote sensing, sustainable management, risk assessment.*

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ДЕГРАДАЦІЯ ҐРУНТІВ У КОНТЕКСТІ ЗБРОЙНОГО КОНФЛІКТУ: КОНЦЕПТУАЛЬНА МОДЕЛЬ

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Повномасштабне військове вторгнення в Україну спричинило екологічну кризу, різко посиливши вже існуючі процеси деградації ґрунтів і створивши нові загрози для ґрунтового здоров'я, функціонування екосистем і національної продовольчої безпеки. Актуальність цього огляду зумовлена безпрецедентним масштабом воєнного впливу, різноманітністю уражених ландшафтів і далекосяжними наслідками для аграрного виробництва й екологічної стабільності. Метою цієї роботи є комплексний синтез сучасних українських і міжнародних досліджень щодо впливу військової діяльності на ґрунти з акцентом на механізмах і зворотних зв'язках, що лежать в основі деградації, спричиненої війною. Методи включають систематичний аналіз літератури, інтеграцію польових і дистанційних даних та оцінку окремих кейсів. Огляд охоплює чотири ключові виміри змін ґрунтової системи: фізичні порушення (ущільнення, ерозія, утворення вирв), хімічне забруднення (важкі метали, вибухові речовини, нафтопродукти), біологічний занепад (втрата мікробного та рослинного різноманіття) та соціальні порушення (покидання земель, зниження продуктивності, ризики для добробуту населення). Результати свідчать, що війна пришвидшує деградацію ґрунтів через численні взаємопов'язані шляхи, що веде до кумулятивних впливів і ризику екологічних "зсувів режиму", коли ґрунти втрачають стійкість і потенціал до відновлення. Наукова новизна роботи полягає в інтегрованій концептуальній моделі, яка чітко поєднує фізичні, хімічні, біологічні та соціальні зворотні зв'язки, спираючись на український і міжнародний досвід. Практична значущість визначається виявленням основних прогалин у знаннях та наголошенням на нагальній потребі міждисциплінарного, системного моніторингу та адаптивного управління. Запропонована модель і рекомендації застосовні не лише для України, а й для усіх регіонів, які зазнають екологічних наслідків збройних конфліктів, і можуть слугувати основою для розробки політики та стратегій відновлення на основі доказів.

***Ключові слова**: ґрунтове здоров'я, стійкість екосистем, деградація земель, військовий вплив, хімічне забруднення, дистанційне зондування, сталий менеджмент, оцінка ризиків.*

Introduction

The full-scale military invasion of Ukraine by the Russian Federation in February 2022 has unleashed an environmental crisis of unprecedented scale and complexity in the heart of Europe. While the humanitarian, economic, and infrastructural consequences are widely recognized, an equally urgent but less visible catastrophe is unfolding beneath our feet: the large-scale degradation of soils–the very foundation of Ukraine's natural wealth, food security, and ecological stability (Baliuk et al., 2017; Голубцов та ін., 2023). The consequences of this crisis are not limited to Ukraine alone, but threaten to destabilize global agricultural supply chains, impact food prices, and increase risks of transboundary environmental pollution throughout the wider region. The war highlights how armed conflict can create long-term soil degradation, with far-reaching implications for international food security and ecosystem resilience.

Soils are not only the primary medium for food and biomass production, but also irreplaceable regulators of ecosystem functions, water quality, carbon storage, and landscape resilience (Baliuk et al., 2017). Ukraine, home to a remarkable diversity of soil types and some of the world's most fertile chernozems, has long been an agricultural powerhouse and a critical contributor to international grain markets. Yet, even before the war, soil degradation processes–erosion, compaction, chemical contamination, organic matter loss–posed major threats to sustainable land use and national food security (Baliuk et al., 2017). Already then, experts warned that the destruction of Ukraine's chernozems would endanger the nation's greatest natural treasure (Балюк і Кучер, 2022).

The ongoing military aggression has dramatically intensified and complicated these processes. Heavy machinery, explosions, fortification construction, mining, and fires have subjected millions of hectares to unprecedented physical, chemical, and biological stresses (Голубцов та ін., 2023). Contamination by heavy metals, explosive residues, oil products, and novel pollutants has been documented at alarming levels, threatening soil health, crop safety, and human well-being. In southern Ukraine, for example, recent assessments have revealed extremely high heavy metal concentrations, to the extent that some territories are considered unsafe for use without complete reclamation or even removal of the topsoil layer due to toxicity (Тонха та ін., 2025).

Direct mechanical damage is no less destructive. Investigations in Chkalivska territorial community showed that prior to the war, local soils were predominantly high-quality chernozems, rich in organic carbon and with excellent fertility. However, spatial analysis and remote sensing during hostilities demonstrated severe damage: shelling, fires, craters, trenches, and compaction by military vehicles degraded nearly one-third of the most fertile soils of this community (Соловей та ін., 2023). Experimental studies further confirm that explosions redistribute soil fractions, increasing the proportion of silt and clay, while compaction from bomb craters and military roads significantly reduces porosity and hinders plant growth. Restorative measures such as deep tillage and agromelioration are thus urgently required to restore agricultural productivity (Пліско та ін., 2023).

Beyond localized destruction, the ecological consequences of warfare are systemic and catastrophic. Previous analyses of conflict in eastern Ukraine showed that military activity damages all components of the environment and severely restricts the state's ability to monitor and control ecological conditions in conflict zones (Лісова, 2017). This lack of oversight, coupled with the intensity of ongoing hostilities, greatly complicates both assessment and recovery.

Further evidence from Sumy region highlights the acute risks posed by contamination. Research revealed significant exceedances of background concentrations of lead, manganese, copper, zinc, cadmium, and nickel in soils exposed to active combat. In some cases, the concentrations of lead were 5.4 times higher than background levels, while manganese and copper exceeded them nearly fivefold. Exceedances of maximum permissible concentrations were also documented for several metals, underscoring the urgent need for monitoring, delineation, and remediation of polluted territories (Зайцев та ін., 2022).

Recent media and scientific reports vividly illustrate the transformation of Ukraine's agricultural landscapes under war conditions. Journalistic and field accounts describe pockmarked fields, widespread land abandonment, and a new reality for rural communities, whose livelihoods and food security are threatened by both direct war hazards and the persistent legacy of soil degradation (Укрінформ, 2022; Bonchkovskyi et al., 2023; Ma et al., 2022). High-resolution satellite imagery and time-series data have revealed clear "hotspots" of cropland abandonment and vegetation loss, directly linking military activity to the collapse of agricultural management (Ma et al., 2022).

Despite ongoing efforts, the scope and mechanisms of soil degradation under modern military pressure remain underexplored and poorly understood (Голубцов та ін., 2023). Recent comprehensive studies and expert assessments emphasize the need for a holistic, integrative approach that considers not only physical and chemical changes, but also biological, social, and economic dimensions. As highlighted by Baliuk et al. (2017), Ukraine urgently requires a science-based, systemic strategy to protect, restore, and sustainably manage its soils–not only to safeguard food production, but to secure national resilience and global ecological stability. Addressing these challenges is essential not only for the immediate recovery of Ukraine, but also for ensuring the long-term stability and productivity of agroecosystems across Eastern Europe and beyond.

This review synthesizes current knowledge on the impacts of military activity on soils, drawing from both Ukrainian and international experience. We propose an integrated conceptual framework for understanding soil system degradation in war-affected landscapes, emphasizing the interactions among physical, chemical, biological, and social factors. In doing so, we aim to inform research, monitoring, policy, and practical intervention to support the recovery and long-term sustainability of Ukraine's land resources.

Material and methods

Analytical approach to the development of the conceptual framework. This review systematically analyzes published research on the impacts of military activities on soils in Ukraine and other countries, synthesizing findings from field, laboratory, modeling, and socio-ecological studies. International research has assessed physical effects–such as compaction, bulk density changes, and erosion–using soil sampling, penetrometry, and mapping (Pichtel, 2012; Krajnović & Smolek, 2024; Ricci et al., 2012). Chemical contamination has been evaluated by measuring heavy metals, petroleum hydrocarbons, and explosive residues with advanced analytical methods (Pichtel, 2012; Vasarevičius & Greičiūtė, 2004) while modeling approaches predict pollutant mobility and bioavailability (Johnson et al., 2011).

Biological and ecological impacts have been studied through assays of soil microbial communities, enzymatic activity, and plant diversity, highlighting the effects of military stress on ecosystem resilience (Rodríguez-Seijo et al., 2024; Bulba et al., 2024). Remote sensing and GIS-based analyses enable mapping of large-scale changes such as crater formation and vegetation loss, especially where field access is restricted (Johnson et al., 2011; Ricci et al., 2012). Socio-ecological dimensions–including land abandonment and agricultural risks–are investigated through surveys, interviews, and risk indices (Akhundov, 2024; Petrushka et al., 2023).

Recent Ukrainian research has adapted these approaches to the realities of ongoing conflict. Rapid soil sampling and contamination assessment are conducted near frontlines (Trokhaniak, 2024), while national-scale mapping and inventories document degraded and contaminated lands (Baliuk et al., 2017; Голубцов та ін., 2023). Comparative studies examine impacts across land use types, and bibliometric analyses highlight key knowledge gaps (Greičiūtė et al., 2007). Collaborative assessments increasingly integrate fieldwork, stakeholder perspectives, and policy analysis (Petrushka et al., 2023).

To develop our integrated conceptual framework, we reviewed over 10 peer-reviewed articles, technical reports, and policy documents from Ukrainian and international sources. Findings were organized into four principal dimensions: physical, chemical, biological, and social. Case studies from Europe, the Middle East, and North America informed our analysis of mechanisms such as heavy metal accumulation, soil structure alteration, and biological decline, as well as context-specific drivers like munitions type and land management history. Key indicators were selected for each dimension based on prevalence in the literature and relevance to Ukraine–e.g., bulk density for physical disturbance, lead and TNT for chemical impacts, microbial biomass for biological effects, and land abandonment rates for social change. The conceptual diagram illustrating these relationships was designed and coded using the Mermaid Chart tool, which enabled a clear and flexible visualization of both direct impacts and system feedbacks. The diagram was refined through iterative expert review and supplemented by recent findings (Голубцов та ін., 2023).

This framework is primarily a synthesis of published knowledge rather than new experimental or modeling work. Empirical data remain limited, especially for long-term recovery, cumulative effects, and effective remediation. We recommend expanded use of remote sensing and GIS, long-term soil health studies, and integration of molecular tools such as metagenomics. Greater involvement of local communities and open-access data sharing will further advance monitoring and restoration efforts.

Results

To address the need for a systems-level understanding of war-related soil degradation, we developed a conceptual model of soil system resilience and degradation under military impact (Figure 1). This model synthesizes Ukrainian and international research and captures the multidimensional and cascading effects of military disturbance on soil.

The framework centers on four domains: physical, chemical, biological, and social.

The physical domain covers processes such as compaction, erosion, and fragmentation, typically resulting from heavy machinery, explosions, and trenching; for example, repeated vehicle traffic and blast craters can irreversibly alter soil structure, decreasing porosity and long-term water infiltration.

The chemical domain encompasses both legacy and novel pollutants–including heavy metals (Pb, Zn, Cd), energetic compounds (TNT, RDX), petroleum hydrocarbons, and altered soil pH–reported in post-war soils from Ukraine and internationally. Persistent contaminants such as lead and explosive residues may accumulate in soil profiles, posing ongoing risks to crop safety and ecosystem health.

The biological domain reflects changes in soil microbial communities, reduced biodiversity, and the spread of invasive species, all of which impact nutrient cycling and plant productivity. Military-induced disturbance can lead to a loss of beneficial microbes, suppress soil enzymatic activity, and facilitate the dominance of stress-tolerant or invasive plant species.

The social domain addresses shifts in land use, such as abandonment, reduced agricultural productivity, and risks to food safety and community health. For instance, the displacement of rural populations and the presence of unexploded ordnance hinder land cultivation, contributing to decreased yields and long-term socio-economic disruption.

The model visualizes the main pathways of influence: for example, physical disturbance affects chemical mobility, chemical contamination drives biological decline, and land abandonment exacerbates degradation through

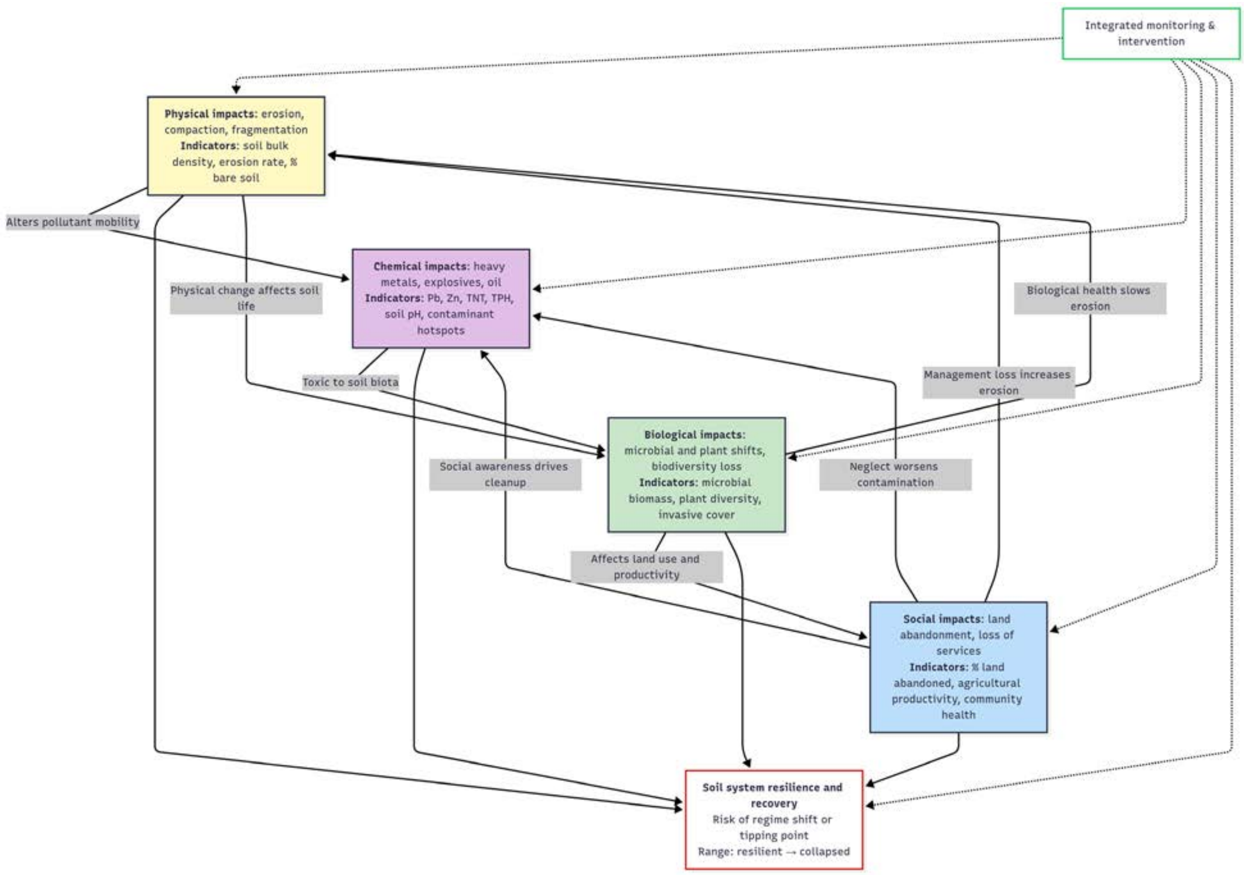

Fig. 1. Integrated conceptual model of soil system resilience and degradation under military impact

feedback loops. At its core is soil system resilience and recovery, representing the combined and interacting pressures from all domains, and highlighting the risk of regime shifts if critical thresholds are crossed. Integrated monitoring and intervention are positioned as cross-cutting requirements, as the literature shows that only coordinated, systems-based strategies can support effective soil recovery where feedbacks are strong.

Overall, the model synthesizes current knowledge and provides a practical framework for future research, monitoring, and intervention in war-affected landscapes–especially in Ukraine, where the scale and complexity of impacts require holistic, adaptive management.

Discussion

The integrated conceptual model presented in this review provides a framework for interpreting the multifaceted impacts of military activity on soil systems. By explicitly mapping the relationships and feedbacks between physical, chemical, biological, and social domains, the model moves beyond reductionist approaches that have characterized much of the prior literature. In the context of the ongoing war, where the scale and diversity of disturbance types are unprecedented, such a systems-oriented perspective is essential. Evidence synthesized from both Ukrainian and international studies confirms that the degradation of soils under military influence is rarely attributable to a single mechanism. Physical disturbance, including compaction, erosion, and soil profile disruption, emerges consistently as an initial driver of change, often resulting from the movement of heavy machinery, fortification building, or explosive impacts. However, these physical processes are closely linked to chemical transformations. Numerous investigations have reported elevated concentrations of heavy metals, explosive residues, and petroleum hydrocarbons in war-affected soils, with physical alteration often enhancing the mobility and persistence of these contaminants (Pichtel, 2012; Vasarevičius & Greičiūtė, 2004). These findings are consistent with research from both Ukraine and other regions with histories of armed conflict, including

France, Lithuania, and Kuwait. The biological dimension, while sometimes underappreciated in initial assessments, is increasingly recognized as critical to both soil health and ecosystem recovery. Studies highlight declines in microbial biomass, shifts in community structure, and reduced plant diversity following military disturbance (Rodríguez-Seijo et al., 2024; Bulba et al., 2024). The disruption of biological processes can constrain natural attenuation of contaminants and reduce resilience, particularly when compounded by physical and chemical stressors. Importantly, the social context emerges as both a mediator and amplifier of soil degradation. Land abandonment and the breakdown of traditional management are recurrent outcomes in areas experiencing prolonged conflict. The literature suggests that the cessation of cultivation and erosion control often accelerates both physical and chemical degradation, while the loss of social capital limits the prospects for remediation and recovery (Baliuk et al., 2017; Petrushka et al., 2023). Conversely, community awareness and engagement–when present–can play a significant role in driving clean-up and restoration initiatives. A major insight arising from this model is the importance of feedbacks among system components. For instance, physical disturbance not only predisposes soils to further chemical contamination but may also trigger biological decline, setting in motion self-reinforcing cycles of degradation. Similarly, social disintegration can hinder both monitoring and intervention, permitting unchecked environmental decline. The risk of crossing ecological "tipping points"–such as the collapse of key soil functions or the establishment of persistent contaminant hotspots–is thus not theoretical, but grounded in empirical observations from war-affected landscapes. At the same time, several limitations of the current knowledge base should be acknowledged. The empirical literature remains fragmented, with relatively few longitudinal studies tracking soil system trajectories beyond the immediate aftermath of war. There is a need for integrated monitoring approaches that combine field surveys, laboratory analysis, remote sensing, and molecular techniques, and for open-access databases to facilitate cross-site comparisons. Furthermore, the social dimensions of soil recovery–particularly the roles of governance, policy, and local knowledge–require further investigation if sustainable restoration is to be achieved. In summary, the proposed framework offers a lens through which to understand the complexity of soil degradation under military impact and provides a foundation for both future research and practical intervention. In the Ukrainian context, where war-related disturbances are ongoing and multi-scalar, such integrative approaches are urgently needed to guide monitoring, remediation, and the long-term protection of soil resources.

Conclusions

This review demonstrates that the degradation of soil systems under military activity is a complex, multidimensional process, shaped by interrelated physical, chemical, biological, and social factors. The integrated conceptual model developed here synthesizes current knowledge and highlights the pathways and feedbacks through which war-related disturbances affect soil health, function, and recovery potential.

Evidence from Ukraine and other war-affected regions underscores the urgency of adopting systems-based approaches to both research and intervention. The framework presented in this study makes clear that piecemeal or domain-specific strategies are insufficient in the face of feedbacks and cascading effects. Instead, coordinated monitoring and management–attentive to cross-domain interactions and the risk of regime shifts–is essential for safeguarding soil resilience and supporting post-conflict recovery.

The current state of research, while advancing, remains limited by a lack of long-term studies and integrative data. Addressing these gaps will require sustained interdisciplinary collaboration, expanded use of advanced monitoring technologies, and greater inclusion of local communities and stakeholders in both assessment and remediation efforts. Policymakers and land managers should prioritize the implementation of integrated soil monitoring systems and adaptive management practices, ensuring that remediation strategies are informed by both scientific evidence and local needs.

Ultimately, the conceptual model proposed here provides a foundation for future empirical research, practical monitoring, and the design of evidence-based policies aimed at the protection and restoration of soils in war-affected landscapes. In the context of Ukraine's ongoing war, the development and application of such integrative approaches is not only scientifically justified, but urgently needed to secure the ecological and socio-economic functions of the country's land resources.

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