EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 75 (2026): 121 - 133
Journal homepage: https://eqa.unibo.it/

published by

Microbial bioindicators of soil recovery potential under anthropogenic transformation

Alla Levishko, Pavlo Mamenko, Oleksandr Kolodiazhnyi, Olena Sherstoboeva, Iryna Gumeniuk*

Institute of Agroecology and Environmental Management of NAAS, Kyiv, Ukraine

* Corresponding author E.mail: gumenyuk.ir@gmail.com

Article info
Received 13/7/2026; received in revised form 27/8/2026; accepted 10/10/2026
DOI: 10.60923/issn.2281-4485/25884
© 2026 The Authors.

Abstract
Amid global climate change and intense human pressure, the planet's land cover is undergoing unprecedented transformation. According to the FAO, over 1.66 billion hectares, more than 10% of the world's land area, have already been degraded through unsustainable use, with over 60% of this occurring on agricultural land. The problem is especially acute in regions affected by military actions and man-made pollution, where physical, chemical, and biological destruction of soils paralyses natural self-purification and the restoration of ecosystem services. This article establishes a comprehensive theoretical and methodological framework for studying anthropogenic soil transformation, systematising global scientific literature and developing an original matrix classification of transformation types that accounts for military and technogenic factors. Through critical analysis of concepts from classical soil science to the modern WRB system, the transition from Anthrosols to Technosols is justified, reflecting anthropogenesis as a dominant factor in soil formation under Anthropocene conditions. Soil microbiota is treated as the most sensitive early bioindicator of anthropogenic stress, capable of determining ecosystems' restorative potential before visible changes appear. The proposed classification is structured around four axes: nature of impact (mechanical, geochemical, biotic, mixed), degree of reversibility, spatial hierarchy, and functional landscape typology. Results confirm that the microbial consortium's functional structure is key to assessing reversibility and reclamation effectiveness. The framework holds significant value for monitoring, mapping and restoring degraded soils, particularly in post-conflict Ukraine, advancing the UN Sustainable Development Goals.

Keywords: *anthropogenic soil transformation, soil microbiota, microorganisms' recovery, military soil degradation, bioindicators, remediation, Technosols, Anthrosols.*

Introduction

In the current context of global climate change, demographic pressure, and intense human-induced stress, the planet's soil cover is undergoing an unprecedented transformation that threatens the achievement of key UN Sustainable Development Goals (in particular, SDG 2 'Zero Hunger', SDG 15 'Protecting terrestrial ecosystems', and SDG 13 'Climate Action'). More than 1.66 billion hectares of land (over 10% of the world's land area) have already been degraded as a result of unsustainable land use, and more than 60% of this degradation occurs on agricultural land (FAO, 2025). Every year, the world loses about 12 million hectares of fertile soil, an area equivalent to that of Bulgaria. These losses lead to a decline in the productivity of agroecosystems, reduced carbon sequestration, and an increased risk of food insecurity for more than 3 billion people. The foundation of any soil's ecological sustainability is its biological activity. However, it is the microbial component of the soil that is most vulnerable to external anthropogenic interventions. Microorganisms provide more than 90% of key ecosystem functions, including the mineralization of organic matter, nitrogen fixation, the degradation of xenobiotics, and the maintenance

The journal is hosted and maintained by AlmaDL. Works are licensed under CC BY 4.0

DOI: 10.60923/issn.2281-4485/25884

of soil structure. At the same time, they are the first to respond to stress, often even before visible morphological or physicochemical changes occur (Fierer, 2017; Romero et al., 2024; Iqbal et al., 2025; Levishko et al., 2026). This issue takes on particular significance in the context of modern military conflicts and large-scale anthropogenic pressure. Hostilities cause comprehensive destruction of the soil profile: physical (mechanical compaction, displacement of soil masses, crater formation), chemical (introduction of heavy metals, pyrogenic compounds, and explosive residues), and biological (a sharp decline in microbial biomass and diversity). According to estimates in the monograph "Soil Cover of Ukraine in the Conditions of Hostilities", a 2.1–3.5-fold decrease in microbial biomass has been observed in areas of active combat operations in Ukraine, and soil toxicity reaches 99% in areas of intense shelling. Similar processes have been documented in studies by Bonchkovskyi et al. (2025), Solokha et al. (2024), and Baliuk et al. (2024) for the northeastern regions of Ukraine, where wartime destruction leads to the formation of specific 'military technosols' (Shebanina et al., 2024). An additional destabilizing factor is anthropogenic pressure caused by the operation of critical infrastructure facilities, the mining industry, urbanization, and intensive agriculture. Under such conditions, classical approaches to soil quality assessment, based primarily on morphological and physicochemical indicators, prove insufficient. It is necessary to rethink the theoretical foundations, with the mandatory inclusion of microbiological indicators as the most sensitive and early markers of anthropogenic stress (Smirnova et al. 2024; Kucher et al. 2025). The issue of anthropogenic soil transformation remains the subject of long-standing scientific debate. Although the impact of traditional agriculture and agrogenesis has been studied in considerable detail, contemporary challenges – including the consequences of hostilities, localized technogenic pollution, and the formation of fundamentally new soil-like bodies (Technosols) – require a deeper theoretical systematization and unification of classification approaches (Shebanina et al., 2024). A significant body of empirical data on land degradation has been accumulated in both international and domestic scientific communities; however, theoretical concepts remain fragmented. Many classification schemes do not account for the specifics of extreme types of impact (pyrogenic, chemical-technogenic, and mechanical-military), and the role of the soil microbiome as a dynamic indicator of transformation and restoration potential is often overlooked (Dror et al., 2021; Pozniak and Telehuz, 2021; Jaroszuk-Sierocińska, 2021). The aim of this study was to develop a comprehensive theoretical and methodological framework for researching anthropogenic soil transformation through a systematic analysis of the global scientific literature and the development of a scientifically grounded classification of the types of such transformation, taking into account the specifics of military and technogenic impact factors and the assessment of the state of the soil microbiota as a key factor in the ecological stability and recovery potential of ecosystems. To achieve this goal, the following tasks must be completed:

- conduct a critical analysis of existing approaches to defining and classifying anthropogenic soil transformation in global scientific literature;
- justify the role of microbiological indicators as the most sensitive and early markers of anthropogenic stress and degradation of the soil environment;
- identify the key factors, mechanisms, and consequences of anthropogenic impact, with a particular emphasis on hostilities and technogenic factors;
- to develop an expanded matrix classification of types of anthropogenic soil transformation that takes into account not only traditional agricultural factors but also extreme technogenic and military factors;
- propose an integrative methodological approach to assessing the degree of soil transformation under various ecological conditions for the purpose of their subsequent reclamation, based on the principles of restoring biodiversity and the functional activity of the microbiome.

The object of the study is the processes of anthropogenic transformation of the soil cover under conditions of intensive land use, industrial development, and hostilities. The subject of the study is the theoretical and methodological foundations for the systematization and classification of types of anthropogenic soil changes, including the transformation of their microbiological component. The methodological framework of this study consists of a set of complementary methods: bibliometric analysis to identify current trends; content analysis and systematization of scientific literature; a comparative-analytical method for comparing different classification approaches; and modelling techniques for integrating anthropological-ecological, landscape-geochemical, and ecosystem paradigms. Thus, the article not only systematizes existing theoretical knowledge but also proposes an original matrix classification model that fills existing

DOI: 10.60923/issn.2281-4485/25884

gaps in the assessment of extreme forms of anthropogenesis and highlights the leading role of the soil microbiome in predicting the recovery potential of degraded areas, particularly in the context of Ukraine's post-conflict recovery.

Anthropogenic soil transformation

The theoretical foundation for research into anthropogenic soil transformation is based on the long-term evolution of scientific perspectives, from classical genetic soil science of the late 19th and early 20th centuries to the contemporary interdisciplinary paradigms of the Anthropocene. This idea was developed into the concept of 'cultural' soil formation and subsequently in the works of soil scientists, who identified agrogenesis as a distinct field of study. In global science, the transition to recognising the anthropogenic factor as an equal factor took place in the second half of the 20th century. A key milestone was the introduction of the terms 'Anthrosols' and 'Technosols' into the international classification system. The modern classification system, the World Reference Base for Soil Resources, focuses on distinguishing materials that have been altered or created by humans. It separates out the Technosols reference group as soils that contain more than 20% artifacts in the top meter-thick layer or that have artificial horizons (Ekranic, Urbic, Spolic, Garbic, etc.). In the last edition of WRB, most of the PQs of the previous edition were maintained (except Hyperskeletic), and Thyric, Gleyic, Stagnic, Coarsic, and Andic were added as PQs. The criteria for horizons containing artefacts and limiting layers at depths of up to 10 cm have also been revised. This reflects the recognition that anthropogenic activity has become an independent and dominant factor in soil formation, capable of completely offsetting the influence of natural factors (parent material, climate). The last edition of WRB, 2022 made small changes to the above provisions the chernic horizon was removed from the list of horizons that, with enough artefacts, would not qualify for Technosols. It was also specified that soils with a limiting layer starting ≤10 cm from the soil surface could be Technosols if the layer consisted of artefacts. There is a problem with undersampling of Technosols, in stark contrast with the high number of qualifiers foreseen in this RSG (Dror et al 2021; Pozniak and Telehuz, 2021; Jaroszuk-Sierocińska, 2021; Hao et al., 2023). Anthropogenic soil transformation refers to a profound qualitative change in the composition, structure and physical, chemical and biological properties of soils under the influence of human activity, leading to the formation of fundamentally new soil-like bodies (urbanised soils, mine spoil heaps, constructed Technosols). It is important to clearly distinguish this process from the narrower term 'degradation', which refers only to negative trends (erosion, salinisation, loss of humus, pollution). Anthropogenic factors (land-use change, tillage, fertilisation and crop rotation) constitute distinct categories of soil transformation, each of which reshapes the structure and functioning of soil microbial communities in its own way. Distinguishing these factors into separate classes is fundamental, as their varying impacts on microbial diversity and biological functions determine the direction and potential for soil recovery (Yang et al., 2021). In the context of intensive industrial activity and hostilities, the study of technosols, where natural soil layers are wholly or partially replaced by artefacts, industrial waste or remnants of munitions, becomes particularly relevant (Volungevičius and Skorupskas, 2011; Howard, 2021; Bonchkovskyi et al., 2025). However, even the most sophisticated classification system based solely on morphological characteristics and the physico-chemical properties of the substrate provides only a static picture of the soil cover's condition. To fully understand the dynamics of changes occurring in anthropogenic ecosystems, it is necessary to consider the functional level of soil organisation, rather than relying on visual assessment alone. In this regard, modern understanding of transformation is impossible without considering the soil microbiota (Epelde et al., 2019; Coban et al., 2022). The microbiome is the most dynamic and sensitive component of soil. It is the first to respond to human-induced stress, even before visible morphological or chemical changes occur (Fierer, 2017; Epelde et al., 2019; Iqbal et al., 2025). Microorganisms provide over 90% of ecosystem functions, including the mineralisation of organic matter, nutrient cycling, degradation of xenobiotics, formation of soil structure, and suppression of pathogens (Romero et al., 2024; Romero et al., 2026). In technogenic and war-damaged soils, 'microbial divergence' occurs, whereby extreme factors such as heavy metals, explosives and compaction radically alter the architecture of microbial networks. This process suppresses symbiotic groups such as mycorrhizal fungi and nitrogen-fixing bacteria, while stimulating the development of resistant taxa such as

EQA 75 (2026): 121 - 133

DOI: 10.60923/issn.2281-4485/25884

metal-tolerant and sulphate-reducing bacteria. Recent metagenomic studies show that the functional diversity of the microbiome in constructed technosols can differ significantly from that in natural soils, and that the addition of compost or microbial inoculants significantly impacts the microbial content (Chialva et al., 2025; Levishko et al., 2026). The microbiological and structural shifts identified require systematic interpretation. Modern science uses several interrelated theoretical models to analyse anthropogenic transformation. The anthroecological model, for example, assesses soil condition in terms of its impact on human health and ecosystem services. This is particularly important in cases of chemical contamination by xenobiotics and war-related pollution. The landscape-geochemical approach focuses on the role of soil as a reservoir and regulator of substance flows. It views transformation as the conversion of natural geochemical barriers into man-made anomalies. The ecosystem model regards soil as a central hub for global ecosystem services, from regulating the carbon cycle to supporting food security. Jenny's soil formation equation is still considered the most comprehensive, as it laid the quantitative foundations of theoretical soil science. In its classical formulation, soil condition is described as a function of five natural factors: S = f (cl, o, r, p, t), where cl is climate, o is organisms, r is relief, p is parent material and t is time (Jenny, 1941). In light of the scale of human influence, this model was modified to include an additional independent anthropogenic factor, a, to account for the intensity, duration, and type of pressure exerted. This approach has made it possible to conceptualise soil formation driven by humans as a distinct process, known as 'anthropogenesis', in which soil is no longer considered purely natural, but rather a human-natural entity (Richter and Yaalon, 2012). Thus, the theoretical foundations of anthropogenic soil transformation have evolved from a static morphogenetic approach to a dynamic, functional ecosystem approach centred on soil microbiota. The authors' matrix classification, which integrates these models, overcomes the fragmented nature of previous schemes, creating a comprehensive toolkit for assessing and forecasting the condition of technogenic and militarily damaged soils, particularly in the context of post-conflict recovery in Ukraine. In order to systematise the global scientific literature on anthropogenic soil transformation, a comprehensive analysis of databases covering the period from 1990 to 2026 was conducted. An analysis of scientific publications in the Web of Science Core Collection (TITLE-ABS-KEY) database, using the terms 'Antrosols', 'Technosols', 'Anthropogenic Soil Transformation', 'Bioindicators', 'War' (or 'Military Soil Degradation'), 'Recovery Potential' and 'Soil Microbiome' (or 'Soil Microorganisms'), revealed that, as of 1 June 2026, 13,874 publications had been indexed (Fig. 1). In addition, a content analysis was carried out on over 450 relevant publications. Around 120 of the most frequently cited and up-to-date works were then selected for detailed study. The bibliometric analysis revealed exponential growth in publication activity, particularly after 2006 when the Technosols reference group was officially incorporated into the World Reference Base for Soil Resources (WRB, 2022). Until 2005, the number of publications remained relatively stable at an average of 15–25 per year, mainly concerning general soil science

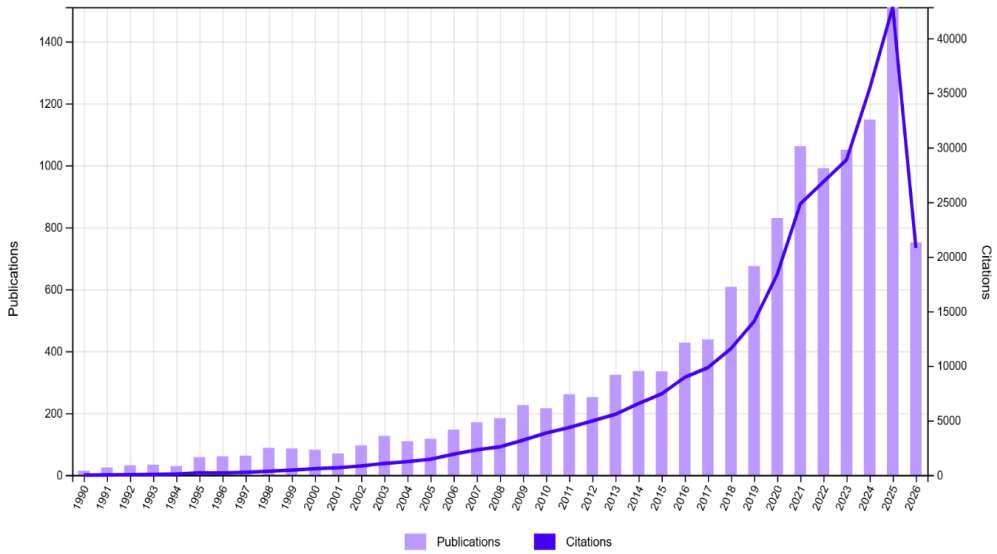


Figure 1
Dynamics of the number of indexed publications in web of science core collection
Source: created by the authors (from 01.06.2026)

EQA 75 (2026): 121 - 133

DOI: 10.60923/issn.2281-4485/25884

and agropedogenesis. Since the 2010s, however, there has been a sharp increase: the peak between 2016 and 2020 (with over 150 research papers published each year) is linked to the recognition of anthropogenesis as an independent dominant factor in soil formation under Anthropocene conditions. A second significant peak is expected between 2022 and 2026 (with over 220–280 publications per year), driven by the WRB 2022 update, the growing concept of 'constructed technosols', and increasing interest in the consequences of military conflicts, particularly in Ukraine. According to WoS data, by the end of 2025, the total number of publications on the topics of 'technosols' and 'anthropogenic soils' had exceeded 2,800, over 45% of which were published after 2018 and are shown in Table 1.

Table 1. *Bibliometric trends in research on anthropogenic soil transformation*

Period	Number of publications (approximate)	Key driving topics	Leading countries	The proportion of work on the microbiome
1990–2005	450–600	Agrogenesis, urban soils	The USA, Germany and China	<10%
2006–2015	1200–1500	The introduction of technosols into the WRB	The USA, China and Spain	15–20%
2016–2021	2200–2600	Constructed technosols, ecosystem services	China, Brazil and the EU	28–35%
2022–2026	>2800	Military technosols, microbiomes and the Anthropocene	Ukraine, the USA, China and the EU	42–48%

The leaders in the number of publications are traditionally the USA, China, Germany, Brazil, Spain and Italy. The most frequently cited research areas were the reclamation of mine waste heaps, urbanised soils, the assessment of ecosystem services provided by Technosols, and the role of the microbiome in the recovery of degraded areas. Ukrainian research is represented by a smaller number of studies (around 180–220), but demonstrates high regional relevance, particularly with regard to the industrial landscapes of the Donbas, Chernobyl and war-damaged areas in the Kharkiv, Chernihiv and Sumy regions (Baliuk et al., 2024; Solokha et al., 2024; Bonchkovskyi et al., 2025). The relevance of this topic is confirmed by the visualisation of the search results, which showed that the majority of publications relate to the fields of 'Environmental Science and Ecology' – 43.2%; 'Agriculture' – 13.6%; and 'Microbiology' – 6.5% (Fig. 2).

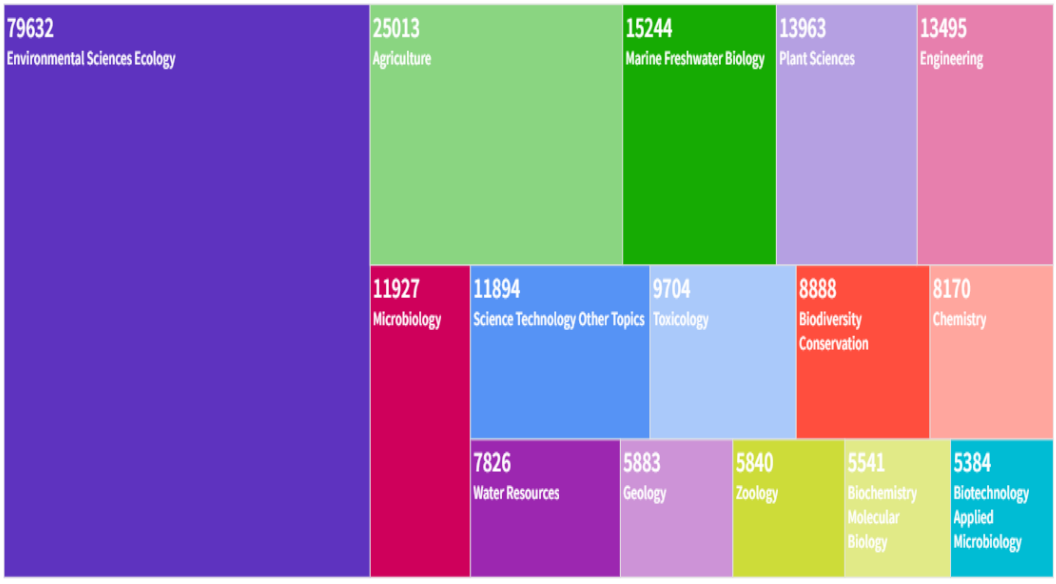


Figure 2
TreeMap visualization of publication dividing in the Web of Science Core Collection (1990–2026)

DOI: 10.60923/issn.2281-4485/25884

Contemporary research covers three key trends in anthropogenic soil transformation: physical aspects (compaction, erosion, structural changes and bomb disturbance in war zones); chemical aspects (accumulation of xenobiotics, heavy metals and explosive residues); and biological aspects (changes in the microbiome and loss or restoration of functional diversity). There is a growing interest in integrative ecosystem models based on the aforementioned modified soil formation formula (Jaroszuk-Sierocińska, 2021; Dror et al., 2021). Conversely, soil is traditionally considered to be a function of climate, organisms, relief, parent material and time, and consequently its internal properties are largely pedogenically determined (Jenny, 1941). Roper et al. (2017) found that soil health indicators did not distinguish between management systems to any great extent, largely because region-specific intrinsic soil constraints outweighed the influence of management. However, there are clear gaps in the literature: insufficient integrated studies combining physical, chemical, and biological transformations in a single, comprehensive analysis; a lack of long-term (over 10 years) Technosol monitoring; weak coverage of the consequences of military destruction (only 8–12% of studies focus on military soils); and insufficient attention to regional characteristics of domestic Chernozems compared to urbanised Western soils. A critical analysis of the methodological approaches employed in prior studies reveals that the majority of research is founded on traditional field and laboratory techniques (e.g. morphological description, chemical analysis and spectroscopy), supplemented by geographic information systems, remote sensing and metagenomics. Modern 'omics' approaches are increasingly being used to characterise soil microbial communities and identify new soil health indicators, providing a promising basis for assessing recovery potential (Delgado-Baquerizo et al., 2018; Clagnan et al., 2024). The strengths include the standardisation of classification in WRB 2022 and the use of the modified Jenny model. However, critical shortcomings remain, including the predominance of chemical indicators over physical and biological ones; the short-term nature of experiments; the lack of a unified, quantitative model of anthropogenic soil formation; the subjectivity of comparing national and international classification systems; and the insufficient integration of anthropo-ecological, landscape-geochemical, and ecosystem models within a single study.

Academic schools and research areas of significance

Western European and North American schools. They play a leading role in developing international classifications and methodologies. A notable accomplishment was the incorporation of the Anthrosols and Technosols reference groups into the WRB 2022 (Ivanyuk et al., 2026). The school is actively developing research areas focusing on urban soils, industrial land reclamation, and ecosystem services within the Soils of Urban, Industrial, Traffic, Mining and Military Areas (SUITMA) initiative framework. Recent studies, notably those by Chialva et al. (2025), have demonstrated that the functional diversity of the microbiome in constructed technosols differs signi-ficantly from that in natural soils. This diversity can be used to improve ecosystem services by inoculating and managing microbial communities.

Asian and Latin American schools. Their focus is on the practical rehabilitation of man-made landscapes following intensive mineral extraction and the accumulation of heavy metals, as well as the restoration of degraded tropical areas. They actively apply international WRB standards, combining them with local biotechnological approaches (Gunathunga et al., 2023).

The Ukrainian School of Soil Science. The works of the Lviv scientific school remain leading in domestic soil science, in particular Pozniak and Telehuz (2021) on the genesis, classification, and properties of soils altered by human economic activity. A fundamental synthesis of the state of the soil cover under wartime conditions is the collective monograph by Baliuk et al. (2024), which systematizes war-related degradation and measures for soil recovery. The empirical direction is represented by studies of the direct consequences of combat operations. Bonchkovskyi et al. (2025), using the example of the Kharkiv region and combining high-resolution remote sensing, soil mapping, and laboratory methods, showed that for chernozems the war-related damage manifests through physical disturbance of the profile and loss of fertility rather than through large-scale heavy-metal contamination, which is noticeable only in localized areas. Solokha et al. (2024), on plots where military vehicles burned, recorded an increase in the sand fraction by a factor of 1.2–1.8 accompanied by a decrease in the silt fraction. Kucher et al. (2025) carried out an ecological-economic assessment of the impact of war on natural resources, in particular on land and soils. A common feature of

DOI: 10.60923/issn.2281-4485/25884

these works is their emphasis on the regional characteristics of chernozems and technogenic landscapes and their substantiation of the complex mechanical, chemical, and biological character of anthropogenic transformation. The proposed methodology, which integrates bibliometric data, matrix-based systematization of transformation types, and modelling that accounts for the intensity of anthropogenic pressure, overcomes the fragmentation of existing approaches and forms a coherent theoretical and methodological basis for further empirical study of the patterns of anthropogenic soil transformation, particularly in the war-affected and post-conflict territories of Ukraine.

The classification of types of anthropogenic soil transformation

The methodological framework for classifying anthropogenically altered soils is based on a comprehensive analysis of the genesis, intensity and depth of penetration of the impact, the duration of its action, and the ecological reversibility of its consequences. This approach recognises human activity as a dominant factor in soil formation under Anthropocene conditions not merely an external one (Jaroszuk-Sierocińska, 2021; Dror et al., 2021; Coban et al., 2022; Chialva et al., 2025; Capra, 2025). Soil degradation is caused by natural and anthropogenic factors; the latter lead to more profound and long-lasting transformations of the soil profile (Lal, 2025). This distinction serves as the primary basis for classifying types of anthropogenic soil transformation. We propose a matrix-based classification scheme for anthropogenic soil transformation with a clear four-axis structure (Fig. 3). This model enables the systematic description, diagnosis, and prediction of technogenic and militarily destroyed soils, filling gaps in existing classifications (WRB, 2022). The matrix structure is based on four strategic axes of analysis:

1. Nature (type) of impact: mechanical, geochemical, biotic or mixed.
2. The degree of reversibility of changes is assessed using a five-point scale ranging from fully reversible (I) to irreversible (V).
3. Spatial hierarchy (scale) of impact: local, regional or global.
4. Functional classification of objects: agricultural landscapes; urbanised areas; industrial and technogenic areas; and militarily destroyed areas.

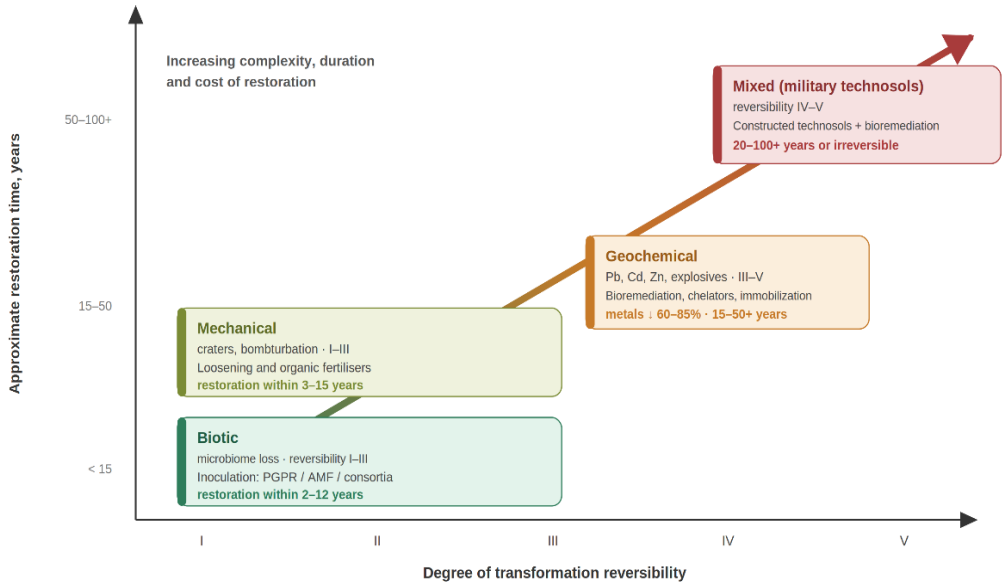


Figure 3
Matrix-based classification scheme for anthropogenic soil transformation types (author's scheme)

A detailed analysis of the main types of transformation using the proposed matrix provides a deeper understanding of the mechanisms of anthropogenic evolution, enabling the development of targeted remediation strategies. Mechanical disturbance leads to the physical destruction of the soil structure and the loss of topsoil, as well as changes in particle size distribution. Under wartime conditions involving bomb disturbance, the sand fraction increases by 1.2–1.8 times, the soil becomes more compacted and craters appear (Solokha et al., 2024; Baliuk et al., 2024; Bonchkovskyi et al., 2025). Geochemical transformation is accompanied by the accumulation of xenobiotics, heavy metals (such as Pb, Cd and Zn), explosive residues and pyrogenic com-

DOI: 10.60923/issn.2281-4485/25884

pounds. This radically alters geochemical barriers and increases toxicity (Baliuk et al., 2024; Kucher et al., 2025). Biological transformation is characterised by the degradation of the soil microbiome, including a 2–3.5-fold reduction in biomass, a shift in the bacteria/fungi ratio, a loss of metabolic potential, and the emergence of resistant taxa (Iqbal et al., 2025; Chialva et al., 2025). Mixed transformation is often irreversible, leading to the formation of technosols where the natural substrate is completely replaced by artefacts or specific substrates. This is particularly relevant in areas of armed conflict, where war-related destruction leads to comprehensive soil degradation and the formation of 'military technosols'. A comparative analysis of the proposed classification against international standards highlights its adaptability and originality (Table 3). The proposed matrix model addresses the lack of assessment of reversibility, scale of impact, and microbiome role, while integrating extreme wartime factors that have only been partially represented in international classifications until now (Dror et al., 2021). While regional studies often consider types of transformation in isolation, the authors' approach unites all types of pressure, from traditional agrogenesis to extreme, war-related destruction, within a single matrix system. This creates a unified theoretical framework for monitoring, mapping and the quantitative assessment of transformed landscapes, as well as the development of reclamation strategies in the current conditions of the Anthropocene. Consequently, the proposed classification not only systematises existing knowledge, but also provides a practical tool for rapidly assessing soil conditions in post-conflict regions of Ukraine. This offers a scientifically sound basis for further developing methodological frameworks and recovery strategies.

Table 3. *A comparative analysis of the assessment of anthropogenically transformed soils*

Comparison criterion	WRB 2022	Ukrainian tradition	Author's matrix scheme
Main focus	Morphology and artefacts (>20%)	Landscape-geochemical barriers	4-axis matrix
Accounting for war-related damage	Partially (SUITMA)	Good	Fully (separate type: 'military technosols')
Microbiome role	Not taken into account	Partial	Central (bioindicator and mediator)
Assessment of reversibility of changes	None	Partial	Full 5-point scale
Practical focus	Mapping	Regional restoration	Monitoring, forecasting and remediation
Adaptability to the Anthropocene	High	High	Highest (integrative)

Development of the theoretical and methodological framework for the study

A theoretical and methodological framework for studying anthropogenic soil transformation has been developed by integrating the results of a systematic analysis of the global scientific literature and the authors' matrix classification scheme into a single, coherent conceptual model. This synthesis allows us to move away from fragmented descriptions of individual aspects of transformation and towards a unified theoretical platform that considers both the morphogenetic and functional-dynamic characteristics of soils in the Anthropocene. According to recent research, in technogenic and militarily destroyed landscapes, the anthropogenic factor often outweighs the influence of natural components, radically altering the trajectory of soil formation and resulting in the formation of new soil-like bodies known as Technosols (Chialva et al., 2025). The central element of the proposed model is a comprehensive analysis of physical, chemical and, in particular, biological transformations. In this analysis, the soil microbiota is regarded as the most sensitive and earliest indicator of anthropogenic changes (Epelde et al., 2019). Current scientific research unanimously confirms that microorganisms act as the 'invisible architects' of the pedosphere, driving biogeochemical cycles, the degradation of xenobiotics, the formation of soil structure, and the maintenance of ecosystem services, even in deeply transformed technosols (Fierer, 2017; Romero et al., 2024; Romero et al., 2026). To evaluate the condition of the soil microbiome in technosols and war-damaged soils, the modern methods presented in Table 4 are recommended.

DOI: 10.60923/issn.2281-4485/25884

Table 4. *Soil microbiome assessment in technogenic and war-damaged soils using modern methods*

Method	Level of analysis	Advantages	Disadvantages	Application in Ukraine (recommendations)
Cultural (traditional microbiological approach)	Species / functional	Isolation of live microbial strains	Low cultivation (1–5%)	Isolation of local PGPR strains
16S rRNA/ ITS metagenomics	Taxonomic	High resolution	Provides no functional information	Diversity monitoring
Shotgun metagenomics	Functional and taxonomic	Complete genomic profile and metabolic pathways	High cost	Assessment of self-purification potential
Metatranscriptomics/ metaproteomics	Functional	Reveals actual microbial activity	Technically difficult	Predicting the potential for regeneration
Enzymatic activity	Functional	Fast, inexpensive, field-based	Indirect indicator	Mandatory screening in monitoring

The proposed theoretical principles are based on recognising anthropogenesis as an independent process and integrating three key approaches: the anthropo-ecological, landscape-geochemical and ecosystemic approaches. The study takes a multidisciplinary methodological approach, paying particular attention to microbiota due to their high reactivity to mechanical compaction, chemical pollution, and war-related destruction (Fierer, 2017; Wolińska et al., 2020; Wang et al., 2024; Shebanina et al., 2024; Levishko et al., 2026). This study's working hypothesis is that the subsequent evolution trajectory and rate of reversibility of changes in Technosols (particularly those subjected to military destruction) are primarily determined by the metabolic state of the microbiocenosis. A resilient system that can self-purify is ensured by the preservation of key functional groups of microorganisms, whilst their suppression leads to an irreversible loss of functionality. A combination of classical and modern methods is used to empirically verify the hypothesis. Field studies involve morphological descriptions of soil profiles according to WRB standards, followed by laboratory physicochemical analysis. The molecular biology component of the study is supported by approaches such as shotgun metagenomics, 16S rRNA gene sequencing, metatranscriptomics, and enzymatic activity analysis. Culture-based methods are employed to isolate promising extremophilic strains. This integrative approach addresses the limitations of previous studies and provides a scientific basis for developing strategies to monitor and sustainably manage soil resources in the face of challenges in the Anthropocene era (Delgado-Baquerizo et al., 2018). In Ukraine, where soil cover has been subjected to a unique combination of industrial and military impacts, the proposed methodology enables the timely assessment of chernozem and sod-podzolic soil conditions, the prediction of reclamation success, and the selection of optimal microbial communities for bioremediation (Ivanyuk et al., 2026). Therefore, the developed theoretical and methodological framework is not only a synthesis of existing knowledge, but also an original set of tools combining matrix classification, a modified version of Jenny's (1941) model and microbiological bioindicators. This framework opens up new prospects for empirical research, practical reclamation, and the development of policies for areas affected by armed conflict (Rodríguez-Rastrero et al., 2023).

Practical relevance and recommendations for soil recovery in Ukraine

The theoretical and methodological framework developed in this study is of fundamental and significant practical importance, particularly for Ukraine. The country's soil cover has been subjected to an unprecedented combination of pre-war anthropogenic pressures and extensive military destruction since 2022. According to several studies (Solokha et al., 2024; Baliuk et al., 2024; Bonchkovskyi et al., 2025), over 2.5–3 million hectares of land have been affected by complex soil degradation as a result of hostilities. This degradation includes physical destruction such as crater formation, compaction and bomb disturbance, chemical contamination by heavy metals (Pb, Cd, Zn and Cu) and explosive residues, and biological suppression of the microbiome. This results in a 2–3.5-fold reduction.

DOI: 10.60923/issn.2281-4485/25884

in biomass. Under these conditions, traditional reclamation methods such as mechanical soil replacement and chemical immobilisation become economically unviable and pose environmental risks. The proposed matrix classification and focus on microbiological indicators enable a shift from merely identifying the problem to developing precise, scientifically sound restoration strategies. The proposed model has several practical applications. Firstly, it allows for the prompt identification of the type and scale of soil transformation in areas impacted by hostilities. Furthermore, the model can predict the soil's recovery potential using microbial bioindicators, eliminating the need for costly chemical and analytical studies and significantly reducing costs and assessment time. Ba-sed on the obtained data, the most suitable combined reclamation methods can be selected, including bioaugmentation, biostimulation, the creation of con-structed technosols and phytomycoremediation. Fi-nally, the developed approach allows for the integra-tion of microbial consortia into national land recovery programmes. The practical recommendations developed based on the authors' matrix and adapted to the regional characteristics of Ukraine (the Chernozem soils of the Forest-Steppe and Steppe zones, the sod-podzolic soils of Polissya, and the technogenic landscapes of the Donbas) are summarised in Table 5.

Table 5. *Practical recommendations for soil recovery according to types of anthropogenic transformation (for conditions in Ukraine)*

Type of transformation (based on the matrix)	Recommended measures (priority)	Microbiome role	Examples of implementation in Ukraine
Mechanical (bombturbation, compaction)	Mechanical loosening and application of organic fertilisers (compost, biochar)	Biostimulation of the indigenous microbiota	Mechanical (bombturbation, compaction)
Geochemical (heavy metals, explosives)	Immobilisation and bioremediation (Bacillus and Pseudomonas bacteria; Aspergillus and Trichoderma micromycetes)	Metal-tolerant strains and EPS producers	Donetsk and Sumy regions (Solokha et al., 2024)
Biotic (loss of the microbiome)	Microbial inoculation (PGPR, AMF, consortia)	Active restoration of functional diversity	Post-war territories in the Chernihiv region
Mixed (military technosols)	Creation of constructed technosols, phytoremediation, and nano- and biotechnologies	Engineered microbial consortia and genetically modified strains	Projects in the Kharkiv region

The recommendations are based on successful international experience, such as the construction of technosols in Europe (Chialva et al., 2025) and the reclamation of mine tailings in China and Brazil, and have been adapted to Ukrainian conditions. For chernozems in particular, the use of indigenous strains of microorganisms (*Bacillus subtilis*, *Pseudomonas fluorescens* and *Trichoderma harzianum*), which have been isolated from local degraded soils, is recommended, as this ensures higher survival rates and synergism with the local microflora. Microbial technologies are 3–7 times more cost-effective than traditional methods. It is estimated that implementing bioaugmentation across 1,000 ha of land damaged by military hostilities replacement. Furthermore, using microbial consortia helps restore ecosystem services such as carbon sequestration and increased fertility and biodiversity.

Thus, the practical significance of the developed theoretical and methodological framework extends far beyond academic interest. It is an effective tool for the rapid restoration of Ukraine's soil cover in the post-conflict period. It facilitates the transition to sustainable land use and ensures food security, thereby contributing to the achievement of the UN Sustainable Development Goals. Implementing these recommendations will minimise the impact of the war on soils and transform degraded areas into model sites for European-standard environmental recovery.

Conclusions

A systematic analysis of the global scientific literature covering the period from 1990 to 2026 revealed a profound evolution in the theoretical concepts surrounding anthropogenic soil transformation. This analysis also made it possible to synthesise existing approaches within a single theoretical and methodolo-

DOI: 10.60923/issn.2281-4485/25884

gical framework. This framework integrates classical genetic concepts of soil formation, the modern international WRB classification and interdisciplinary Anthropocene paradigms, in which soil microbiota are simultaneously regarded as dynamic indicators and mediators of transformational processes. The analysis confirmed that the anthropogenic factor in modern soil formation models has lost its secondary status and has become equally important; indeed, in technogenic and militarily destroyed landscapes, it often becomes the dominant factor. A synthesis of the accumulated data provided the basis for developing a matrix classification scheme built on four axes: the nature of the impact; the degree of reversibility of changes; spatial hierarchy; and the functional typology of landscapes. The matrix classification scheme's fundamental novelty lies in its inclusion of extreme military destruction (bombturbation, chemical and pyrogenic contamination) as a distinct type of anthropogenesis. This leads to the formation of specific 'military technosols', and introduces quantitative criteria for assessing the reversibility of transformational processes. The analysed sources pay particular attention to the soil microbiome as the most sensitive and earliest bioindicator of anthropogenic stress. Microbial communities respond to mechanical compaction, chemical pollution and war damage even before visible morphological and physicochemical changes occur, while also ensuring the vast majority of soil ecosystem functions. Synthesised metagenomic and functional studies suggest that preserving key functional groups of microorganisms determines whether Technosols evolve towards self-purification or irreversible degradation. A review of existing scientific findings therefore confirms the emergence of a new research paradigm in which anthropogenic soil transformation is viewed as a multi-level process and soil microbiota become the central focus for diagnosing its mechanisms. Systematising this knowledge provides a conceptual foundation for transitioning from merely noting degradation to understanding the patterns of soil transformation in the face of the challenges of the Anthropocene.

References

BALIUK S.A., KUCHER A.V., ROMASHCHENKO M.I. (Eds.) (2024) Soil cover of Ukraine in the conditions of hostilities: State, challenges, activities for soil restoration. Agrarna nauka (In Ukrainian). https://doi.org/10.31073/978-966-540-612-9

BONCHKOVSKYI O., OSTAPENKO P., BONCHKOVSKYI A., SHVAIKO V. (2025) War-induced soil disturbances in north-eastern Ukraine (Kharkiv region): Physical disturbances, soil contamination and land use change. Science of the Total Environment, 964: 178594. https://doi.org/10.1016/j.scitotenv.2025.178594

CAPRA G.F., GANGA A., GRILLI E., VACCA S., BUONDONNO A. (2015) A review on anthropogenic soils from a worldwide perspective. Journal of Soils and Sediments, 15: 1602-1618. https://doi.org/10.1007/s11368-015-1110-x

CHIALVA M., MASSON S., BONGIOVANNI D., VOTTA C., BARNI E., PADOAN E., STEFANINI I., FIORILLI V., LARCHER F., LANFRANCO L. (2025) Effect of a constructed technosol on the microbial functional diversity in an urban afforestation site. Urban Forestry and Urban Greening, 115: 129179. https://doi.org/10.1016/j.ufug.2025.129179

CLAGNAN E., COSTANZO M., VISCA A., DI GREGORIO L., TABACCHIONI S., COLANTONI E., SEVI F., SBARRA F., BINDO A., NOLFI L., MAGARELLI R.A., TRUPO M., AMBRICO A., BEVIVINO A. (2024) Culturomics- and metagenomics-based insights into the soil microbiome preservation and application for sustainable agriculture. Frontiers in Microbiology, 15: 1473666. https://doi.org/10.3389/fmicb.2024.1473666

COBAN O., DE DEYN G.B., VAN DER PLOEG M. (2022) Soil microbiota as game-changers in restoration of degraded lands. Science, 375(6584): abe0725. https://doi.org/10.1126/science.abe0725

DELGADO-BAQUERIZO M., OLIVERIO A.M., BREWER T.E., BENAVENT-GONZÁLEZ A., ELDRIDGE D.J., BARDGETT R.D., MAESTRE F.T., SINGH B.K., FIERER N. (2018) A global atlas of the dominant bacteria found in soil. Science, 359(6373): 320-325. https://doi.org/10.1126/science.aap9516

DROR I., YARON B., BERKOWITZ B. (2021) The human impact on all soil-forming factors during the Anthropocene. ACS Environmental Au, 2(1): 11-19. https://doi.org/10.1021/acsenvironau.1c00010

EPELDE L., LANZÉN A., MARTÍN I., VIRGEL S., MIJANGOS I., BESGA G., GARBISU C. (2019) The microbiota of technosols resembles that of a nearby forest soil three years after their establishment. Chemosphere, 220: 600-610. https://doi.org/10.1016/j.chemosphere.2018.12.164

FAO (2025) The State of the World's Land and Water Resources for Food and Agriculture 2025 (SOLAW 2025). Food and Agriculture Organization of the United Nations. https://openknowledge.fao.org/items/183921be-218f-4e89-b8db-b9e68d702513

DOI: 10.60923/issn.2281-4485/25884

FIERER N. (2017) Embracing the unknown: Disentangling the complexities of the soil microbiome. Nature Reviews Microbiology, 15(10): 579-590. https://doi.org/10.1038/nrmicro.2017.87

GUNATHUNGA S.U., GAGEN E.J., EVAN P.N., ERSKINE P.D., SOUTHAM G. (2023) Anthropedogenesis in coal mine overburden: The need for a comprehensive, fundamental biogeochemical approach. Science of the Total Environment, 892: 164515. https://doi.org/10.1016/j.scitotenv.2023.164515

HAO S., WU K., LI L., LI X., WEI H., WU X., LIU B. (2023) Classifications for Typical Anthropogenic Soils in China. Land, 12: 1974. https://doi.org/10.3390/land12111974

HOWARD J.L. (2021) Urban anthropogenic soils – A review. In D. L. Sparks (Ed.), Advances in Agronomy, 165: 1-57. Academic Press. https://doi.org/10.1016/bs.agron.2020.08.001

IQBAL S., BEGUM F., NGUCHU B.A., CLAVER U.P., SHAW P. (2025) The invisible architects: Microbial communities and their transformative role in soil health and global climate changes. Environmental Microbiome, 20(1): 36. https://doi.org/10.1186/s40793-025-00694-6

IUSS WORKING GROUP WRB (2022) World Reference Base for Soil Resources 2022: International soil classification system for naming soils and creating legends for soil maps (4th ed.). International Union of Soil Sciences. Retrieved from: https://www.fao.org/soils-portal/data-hub/soil-classification/world-reference-base/en/

IVANYUK H., YAMELYNETS T., PAPISH I., HNATIV P., PANKIV Z., BONISHKO O., IVANIUK V., HASKEVYCH O., BARANSKYI D., AVHUSTYNOVYCH M. (2026) Soil classification of Ukraine and its correlation with WRB (2022). Soil Science Annual, 77(1): 215263. https://doi.org/10.37501/soilsa/215263

JAROSZUK-SIEROCIŃSKA M. (2021) Analysis of Sorption Properties of Anthrosols in the Park Ludowy in Lublin. Journal of Ecological Engineering, 22(11): 86-91. https://doi.org/10.12911/22998993/142911

JENNY H. (1941) Factors of Soil Formation: A System of Quantitative Pedology. Dover Publications, New York.

KUCHER A., SHAIDA O., KUCHER L., KRUPIN V., LOMOVSKYKH L., KOSOVSKA V., WOJCIECHOWSKA A. (2025) Assessing the impact of the Russian-Ukrainian war on nature: New challenges to sustainable development. Journal of Water and Land Development, 67(10–11): 192-203. https://doi.org/10.24425/jwld.2025.156052

LAL R. (2025) Soil Degradation and Pollution as the Global Public Health Emergency. Medical Research Archives, 13(5): 1-11. https://doi.org/10.18103/mra.v13i5.6474

LEVISHKO A., GUMENIUK I., SHERSTOBOEVA O. (2026) Soil microorganisms as bioindicators of agroecosystem condition: a review of their ecological and trophic groups, functional roles, and the impact of anthropogenic factors. EQA International Journal of Environmental Quality, 73: 72-84. https://doi.org/10.60923/issn.2281-4485/24117

POZNIAK S.P., TELEHUZ O.V. (2021) Anthropogenic Soils. Ivan Franko National University of Lviv (In Ukrainian). https://geography.lnu.edu.ua/wp-content/uploads/2021/05/Pozniak-Telehuz-Antropohenni-grunty_book.pdf

RICHTER D.D., YAALON D.H. (2012) The Changing Model of Soil Revisited. Soil Science Society of America Journal, 76: 766-778. https://doi.org/10.2136/sssaj2011.0407

RODRÍGUEZ-RASTRERO M., ORTEGA-MARTOS A., CICUÉNDEZ V. (2023) Soil and Land Cover Interrelationships: An Analysis Based on the Jenny's Equation. Soil Systems, 7(2): 31. https://doi.org/10.3390/soilsystems7020031

ROMERO F., LABOUYRIE M., ORGIAZZI A., BALLABIO C., PANAGOS P., JONES A., TEDERSOO L., BAHRAM M., GUERRA C.A., EISENHAUER N., TAO D., DELGADO-BAQUERIZO M., GARCÍA-PALACIOS P., VAN DER HEIJDEN M.G.A. (2024) Soil health is associated with higher primary productivity across Europe. Nature Ecology & Evolution, 8(10): 1847-1855. https://doi.org/10.1038/s41559-024-02511-8

ROMERO F., LABOUYRIE M., ORGIAZZI A., BALLABIO C., PANAGOS P., JONES A., TEDERSOO L., BAHRAM M., EISENHAUER N., SÜNNEMANN M., GUERRA C.A., TAO D., ROG D., JIAO S., MOCALI S., RILLIG M.S., LEHMANN A., DELGADO-BAQUERIZO M., VAN DER HEIJDEN M.G.A. (2026) The soil microbiome as an indicator of ecosystem multifunctionality in European soils. Nature Communications, 17: 705. https://doi.org/10.1038/s41467-025-67353-9

ROPER W.R., OSMOND D.L., HEITMAN J.L., WAGGER M.G., REBERG-HORTON S.C. (2017) Soil health indicators do not differentiate among agronomic management systems in North Carolina soils. Soil Science Society of America Journal, 81(4): 828–843. https://doi.org/10.2136/sssaj2016.12.0400

SHEBANINA O., KORMYSHKIN I., BONDAR A., BULBA I., UALKHANOV B. (2024) Ukrainian soil pollution before and after the Russian invasion. International Journal of Environmental Studies, 81(1), 208–215. https://doi.org/10.1080/00207233.2023.2245288

SMIRNOVA K., BALIUK S., KUCHER A., VOROTYN-

DOI: 10.60923/issn.2281-4485/25884

TSEVA L., HONCHAROVA A. (2024) Ecological and toxicological condition of militarily degraded chernozems: A case study of the Chkalovsk territorial community. Scientific Horizons, 27(11): 90–104. https://doi.org/10.48077/scihor11.2024.90

SOLOKHA M., DEMYANYUK O., SYMOCHKO L., MAZUR S., VYNOKUROVA N., SEMENTSOVA K., MARIYCHUK R. (2024) Soil degradation and contamination due to armed conflict in Ukraine. Land, 13(10): 1614. https://doi.org/10.3390/land13101614

VOLUNGEVIČIUS J., SKORUPSKAS R. (2011) Classification of anthropogenic soil transformation. Geologija, 53(4):165-177. https://doi.org/10.6001/geologija.v53i4.1904

WANG X., CHI Y., SONG S. (2024) Important soil microbiota's effects on plants and soils: A comprehensive 30-year systematic literature review. Frontiers in Microbiology, 15: 1347745. https://doi.org/10.3389/fmicb.2024.1347745

WOLIŃSKA A., WŁODARCZYK K., KUŹNIAR A., MARZEC-GRZĄDZIEL A., GRZĄDZIEL J., GAŁĄZKA A., UZAROWICZ Ł. (2020) Soil microbial community profiling and bacterial metabolic activity of technosols as an effect of soil properties following land reclamation: A case study from the abandoned iron sulphide and uranium mine in Rudki (South-Central Poland). Agronomy, 10(11): 1795. https://doi.org/10.3390/agronomy10111795

YANG T., LUPWAYI N., ST-ARNAUD M., SIDDIQUE K.H.M., BAINARD L.D. (2021) Anthropogenic drivers of soil microbial communities and impacts on soil biological functions in agroecosystems. Global Ecology and Conservation, 31: e01521. https://doi.org/10.1016/j.gecco.2021.e01521