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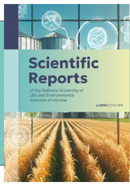

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Phytoremediation of soils contaminated as a result of military and anthropogenic impact

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Abstract. Military conflicts and anthropogenic accidents cause significant soil contamination with heavy metals, oil products, pesticides, and other toxic substances. The purpose of this study was to highlight the factors of influence of military-anthropogenic load on soils and to analyse the available methods of their remediation. The study summarised the available and promising phytoremediation methods with an assessment of their impact on soil contamination by chemicals that are typical pollutants during military conflicts. The study summarised, classified, and compared the groups of pollutants that are most common during military operations; analysed the impact of pollutants on the fertile soil layer and their mobility; and analysed the available remediation methods. It was found that the available soil remediation technologies, which can be used individually or in combination, provide the necessary tools to address the problem of chemical contamination of soils due to toxic products such as explosive derivatives and heavy metals. The degree of economic feasibility was considered, which, accordingly, suggested that soil phytoremediation may be the most economically feasible under certain conditions. This opens wide possibilities for further investigations, where the synergy of ecology, economics, and agrobiology will enable the development of mechanisms for optimising soil phytoremediation methods, considering their type, profile, and intended use. An algorithm of actions for remediation of soils as a result of military-anthropogenic load was proposed, which includes a related set of related actions on zoning, demining, assessment, and return of land to industrial use. The findings of this study can be used to clean industrial areas that have been contaminated during production processes or accidents

Keywords: soil remediation; phytoremediation; anthropogenic impact; soil degradation; chemical soil pollution; energy-intensive substances; propellants

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Introduction

Restoring soil fertility affected by military operations, as one of the most aggressive anthropogenic factors, and protecting it from pollution is a complex scientific challenge of modern time that requires a balanced approach and covers physical, chemical, and biological aspects. The development of new methods of remediation of soils contaminated with both explosives and fuels and lubricants is relevant and significant both in practical and theoretical terms. Phytoremediation is one of the most promising ways to decontaminate xenobiotics in soil using phytoremediation plants. This method does not require physical soil movement, helps preserve the natural environment and soil ecosystem, improves soil quality, protects it from erosion, and can be applied on an industrial scale with a positive economic effect.

Issues related to the impact of anthropogenic military activity on ecological systems continue to be comprehensively investigated by both Ukrainian and foreign scientists. Iu. Boretska *et al*. (2021) investigated the problem of restoring soil fertility and protecting it from pollution using phytoremediation methods and provided recommendations for the use of crops as phytoremediation agents. The researcher noted the effectiveness of some plant species in absorbing heavy metals and toxic substances, which allows not only cleaning the soil but also increasing its fertility for further agricultural use. V. Dudar (2023) covers the issue of military-anthropogenic impact on the environment, considering explosives and their impact on the soil ecosystem. The study noted that explosive remnants of war have a significant negative impact on the environment. They contaminate soil and water resources with toxic chemicals released during explosions and ammunition decomposition. This leads to degradation of natural ecosystems and loss of biodiversity in the affected regions. Furthermore, the presence of explosive remnants of war makes it difficult to access land resources and use them for agricultural and recreational purposes.

Ya. Tsytsiura *et al*. (2022) covered the issues related to the redistribution of heavy metals in the agricultural landscape under the influence of anthropogenic factors and the specific features of their accumulation in plants. The researchers conducted a comprehensive assessment of existing factors, their grouping, and classification. The researchers analysed approaches to phytoremediation and phytoremediation in modern farming systems, which include the use of genetically modified plants that can absorb and neutralise pollutants more effectively. The cited study also used multi-component plant complexes to help clean soils more quickly and comprehensively. These techniques not only increase agricultural productivity but also help to restore ecological balance in agricultural landscapes. Along with Ukrainian scientists, the problem of the impact of military-anthropogenic load is being studied by their foreign counterparts. J.J. Pichtel (2012) examined the distribution and ways of spreading chemical pollutants in the soil, paying special attention to explosives, which are most often used during military and anthropogenic impact. C.R. Müller *et al*. (2022) analysed the impact of mechanical factors on the soil during military exercises, which to some extent serves as a simulation of military-anthropogenic load on the soil system. The study showed that such factors cause considerable changes in the soil structure, including compaction, reduced porosity, and disturbance of the water regime. These changes can lead to soil degradation, reduced fertility, and a negative impact on vegetation and microbiological processes. D. Averin *et al*. (2024), in collaboration with the OSCE (Organisation for Security and Cooperation in Europe) and the Conflict and Environment Observatory, thoroughly examined the environmental consequences of the war in Ukraine. The report analysed the factors of influence, the scale and consequences of ecosystem contamination, including land, and provided recommendations on the possibility of remediation.

To analyse the existing military-anthropogenic impact on soil in Ukraine, it is considered that this impact is not static and is constantly changing. This creates the need for further monitoring of both the factors of influence and its consequences. The purpose of this study was to highlight the factors of phytoremediation impact on soils subjected to military-anthropogenic load. The objectives of the study were to summarise phytoremediation techniques and analyse their impact on soil contamination by chemicals, which are typical pollutants during military conflicts.

For this, a series of general scientific methods were employed, including classification, which was used to group the factors of military-anthropogenic impact and sources of pollution. Using the analytical method, the study investigated the totality of the consequences of negative impact on the soil ecosystem, dividing the latter into mechanical, chemical, and biological. The use of a combination of analytical and theoretical methods helped to propose an action algorithm designed to ensure remediation of soils damaged as a result of military and anthropogenic impact.

Considering the dynamism of military-anthropogenic impact processes and a wide series of factors, the issue of their assessment and classification is a task that aims to create standardised mechanisms for remediation that optimises the process of returning contaminated land to industrial production. Considering that Ukraine's agricultural land is the mainstay of agricultural production, remediation of contaminated soils will have a positive impact on the global food security situation. Thus, soil remediation should be considered not only as a technique, but also as a tool that will serve to improve food security (UNCG 2022).

Types of Soil Damage Depending on the Factors of Influence

Soil damage resulting from military operations is mainly of three main types: mechanical, chemical, and biological – as a result of direct damage or, more often, indirect impact (Certini *et al.*, 2013).

Mechanical damage to the soil includes compaction resulting from the construction of defence infrastructure and facilities, the construction of trench systems, compaction caused by the movement of military equipment, or the formation of craters from detonations of highly explosive substances. Such actions drastically change the structure of the soil profile. Bombardment and shelling create sinkholes, mix soil horizons, and disrupt the water balance. The consequences of such actions are changes in the topography and landscape of the ecosystem (Anderson & Walker, 2000). Almost always, considerable fires occur near the sites of hostilities, causing the burning of fertile soil and the destruction of protagonistic microflora (Agrilab, 2022). The main types of mechanical damage to soils during military operations are (but are not limited to) listed in Table 1:

***Table 1.** The effects of mechanical damage on the soil ecosystem*

Root cause of mechanical soil damage	Implications for the soil ecosystem
1. Movement of heavy machinery	J soil compaction; J aeration disorder; J fuel and lubricants entering the soil.
2. Digging fortifications (trenches, dugouts, emplacements)	J disturbance of the soil profile; J aeration disorder; J soil erosion; J change in relief; J destruction of habitats.
3. Explosions of ammunition	J disturbance of the soil profile; J mixing of soil horizons; J fires.

Source: compiled by the author of this study based on R.M. Iverson (1981), P.S. Althoff & S.J. Thien (2005)

Chemical damage is caused by the ingress of harmful substances into the soil, such as oil and its derivatives, heavy metals, explosives, organophosphates, radioactive elements, etc. Chemical compounds that get into the soil cause serious pollution. Typically, chemicals are not biodegradable and contain a wide range of chemical compounds that are toxic to plants, animals, and humans. They lead to soil contamination, slow plant growth, and threaten the entire ecosystem (Table 2). Such contamination can have long-term effects on the soil ecosystem, the environment, and human health. The impact of chemical soil contamination on both plants - for which access to water and nutrients is impaired – and human health is noted, due to the entry of chemical contaminants into food chains through contaminated plants and water sources (Boretska *et al.*, 2021).

Table 2. *Effects of chemical damage on the soil ecosystem*

Root cause of chemical soil damage	Implications for the soil ecosystem
1. Fuel and lubricants entering the soil	J entry into ground, groundwater, and surface water; J impact of chemical toxicity; J disruption of the water-air balance; J reduction of the water retaining capacity of the soil; J hydrophobic treatment of soil particle surfaces with heavy hydrocarbon fractions; J inhibition of biological processes in the soil; J reduction of soil pore space; J excessive absorption of solar radiation.
2. Explosions of ammunition	J chemical products of the explosion reaction entering the soil; J soil contamination with heavy metals; J thermal and chemical burns of plants; J disturbance of the soil profile; J mixing of soil horizons.
3. Fires	J emission of pollutants into the atmosphere (products of organic synthesis, phosphorus); J contamination of ground and underground water with heavy metal salts (cadmium, etc.); J soil contamination with dioxins, phosgenes, polycyclic aromatic organic compounds; J destruction of vegetation.

Note: FL – fuels and lubricants

Source: compiled by the author of this study based on Iu. Boretska *et al*. (2021)

Biological damage to soil can occur as a result of actions that affect the chemical and physical properties of the soil, as well as through the deliberate introduction of pathogenic cultures of microorganisms that can be deadly to higher animals and humans, such as botulinum or anthrax. Soil is an environment where such pathogens can stay virulent for decades. The presence of pathogens in soil can cause diseases in plants, animals, and humans (Table 3).

Table 3. *The effects of biological damage on the soil ecosystem*

Root cause of biological soil disturbance	Implications for the soil ecosystem
1. Deliberate introduction of pathogenic microorganisms into the soil	J pollution of groundwater and surface water; J increase in the virulence of the soil; J soil intoxication due to pathogenic microorganisms; J changes in the soil microbiome and an increase in the population of pathogens in it.
1. Decomposition of organic residues	J contamination of groundwater and surface water with pathogens; J epidemic consequences; J soil contamination.

Source: compiled by the author of this study based on O. Angurets *et al*. (2023)

Considering the above, the areas affected by active hostilities can be considered as having suffered from contamination of both terrestrial and soil ecosystems.

Typical Pollutants During Military-Anthropogenic Impact on Soil

Scientific research suggests that wars or even military exercises leave behind large areas contaminated mainly with toxic substances such as explosives, ammunition, and their residues (Beckmann & Vykhor, 2022). Examples of such contaminants, which include a large list of organic and inorganic toxic substances in the soil and pose significant risks to agriculture and, subsequently, to human health, are toxic elements released in explosion reactions. Typically, most of these elements are resistant to biodegradation and stay in the ecosystem and become a source of environmental pollution, exerting toxic effects on soil microbiota and water resources (Reuveny *et al.*, 2010). When oxidised in contact with the environment, these toxic elements sometimes become available in the context of their mobility to agricultural plants, and thus potentially dangerous to humans and animals. The consequences of the ingestion of toxins accumulated by plants into living organisms can be damage to vital organs and functions of the organism (Gorecki *et al.*, 2017). Notably, the so-called "Energy materials" are considered a generalised category of pollutants. Energy-intensive substances include both the explosives themselves and the fuels and lubricants mentioned above. When explosives enter the soil, they become xenobiotic pollutants that pose a toxic hazard to the ecosystem (Table 4). Many soils in the world are contaminated with energy-intensive materials as a result of military conflicts, military training exercises at training grounds and demining with open detonations of unexploded ordnance. When energy-intensive materials enter the soil, they undergo varying degrees of chemical and biochemical transformations depending on the chemical compounds they contain and environmental factors. Particular attention should be paid to the most common explosives 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (Hexagen or RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (Octogen or HMX), as well as rocket fuel components: (Nitroglycerin or NG), (Nitroguanidine or NQ), (Nitrocellulose or NC), (DNT or Dinitrotoluene), and perchlorate. These energy-intensive substances are most often used in the production of conventional ammunition, and subsequently – in combat operations or military training.

Table 4. *Explosive decay products and their mobility in soil*

Explosive substance (Energy-intensive substance)	Chemical class of the substance	Type of explosive	Degradation products	Mobility in the soil	Research
2,4,6-trinitrotoluene (TNT)	Organic nitrobenzene	Secondary / explosive filler	Degrades to (2-amino-4,6-dinitrotoluene, 4-amino-2,6-dinitrotoluene)	Often found in the upper soil layers	J.C. Pennington & J.M. Brannon (2002), F. Monteil-Rivera *et al.* (2009), H. Ryu *et al.* (2009), J. Pichtel (2012)
2,4-Dinitrotoluene (DNT)	Organic nitrobenzene	Secondary/ explosive filler or TNT degradation product	Degrades to (2-amino-4-nitrotoluene, 2,4-diaminotoluene, 4-amino-2-nitrotoluene, dinitrophenol)	Mobile in the soil. Enters groundwater. More mobile in sandy soils	ATSDR (n.d.), F. Monteil-Rivera *et al.* (2009), R. Reuveny *et al.* (2010), J. Akhavan (2011), J.D. Arthur *et al.* (2017), T. Temple *et al.* (2018)

Table 4. *Continued*

Explosive substance (Energy-intensive substance)	Chemical class of the substance	Type of explosive	Degradation products	Mobility in the soil	Research
Picric acid	Organic nitrobenzene	Secondary / explosive filler	Stable in water, degrades to toxic and mutagenic degradation products	High mobility in the soil, will stay in the environment for a long time	S.L. Yost *et al*. (2007), F. Monteil-Rivera *et al*. (2009), R.M. Hebert & A. Jackovitz (2015), Q.J. Zhao (2020)
2,4,6-Trinitrophenyl-methyl-nitramine (Tetryl)	Organic nitrobenzene	Secondary / explosive filler	Rapid degradation in soil, comparable to other nitrobenzene products: within a few weeks in some soil types	Mobile in the soil. Enters groundwater	ATSDR (n.d.), F. Monteil-Rivera *et al*. (2009); J.C. Lipcomb (2013), D. DeTata *et* al. (2013)
Cyclotrimethylene trinitramine RDX (Hexogen)	Organic nitramine	Secondary / explosive filler	Degrades to (mono-, di- and trinitroso products MNX, TNX and DNX	Mobile in the soil. Enters groundwater	J.C. Pennington & J.M. Brannon (2002), US Army Corps of Engineers, Environmental Research and Development Center (2006), H. Ryu *et al*. (2009), F. Monteil-Rivera *et al*. (2009)
1,3,5,7- tetranitro -1,3,5,7- Tetrazocaine HMX (Octogen)	Organic nitramine	Secondary / explosive filler	Very slow/ Inconsiderable degradation.	Can enter groundwater and persist for a long time	J.C. Pennington & J.M. Brannon (2002), E.T. Urbansky (2002), US Army Corps of Engineers, Environmental Research and Development Center (2006), H. Ryu *et al*. (2009), F. Monteil-Rivera *et al*. (2009), Technical Fact Sheet Perchlorate (2014), M.R. Sijimol *et al*. (2015)
Nitrocellulose	Polymer	Propellant	Degradation to nitrate and nitrite	Mobility in the soil is improbable	H. Ryu *et al*. (2009), M. Williams (2015), Integrated Risk Information System (1990)
Nitroguanidine	Organic	Propellant	Degrades to less harmful minerals	Mobile in the soil. Enters groundwater	Integrated Risk Information System (1990), F. Monteil-Rivera *et al*. (2009), T. Temple *et al*. (2018)

Source: compiled by the author of this study based on the data of the sources cited in the table

The absorption of pollutants by plants from the soil is influenced by two groups of factors: mobile forms of pollutant elements in the soil, which are regulated by the biological characteristics of plants and the properties of the soil with respect to pollutant ions. The absorption of heavy metals by plants and the simultaneous impact of this process on the soil is twofold. On the one hand, during absorption, the soil reduces the amount of accumulated elements in the plant. However, on the other hand, the accumulation of occluded elements in the upper layers, where the highest concentration of roots is found, facilitates their assimilation by plants and intensive accumulation than in the case of free movement of heavy metals to deeper soil layers.

Classification of Remediation Methods and Their Impact on Xenobiotics

The clean-up of soil contaminated by military operations is a relevant and significant issue for Ukraine. Plants can accumulate xenobiotics in their biomass, which are chemical compounds present in the environment but not part of the normal biological metabolism of the soil ecosystem. Accumulated xenobiotics are metabolised by the plant and absorbed on its surface. That is why phytoremediation can be a relevant and promising method of remediating chemically contaminated and degraded soils in Ukraine. As an actively developing area of soil remediation, phytoremediation combines a considerable number of methods based on the following processes (Table 5):

Table 5. *Methods of phytoremediation*

Phytostabilisation	This process involves the immobilisation of organic and inorganic pollutants in the soil. Plants adsorb these pollutants with their roots or soil particles and deposit them in the root zone. After that, xenobiotics turn into insoluble, inactive forms that stay in the soil complex. This prevents them from moving in soil, water, or air. Phytostabilisation also reduces erosion, agricultural and chemical leaching, contributing to the restoration of ecosystems and biodiversity.
Phytoextraction	This method is used for the absorption of xenobiotics by the root system of plants. Plants absorb pollutants along with nutrients and then transfer them to their aboveground parts. At the end of the growing season, the plants are mowed and processed accordingly. This helps cleanse the soil of the effects of heavy metal and radionuclide contamination.
Phytostimulation	This process increases microbial metabolism in the plant rhizosphere. Microorganisms living near the roots of plants actively decompose pollutants, contributing to the purification process. Phytostimulation can include the use of microbial cultures or special fertilisers that support the development of the necessary beneficial bacterial and fungal cultures in the soil. Furthermore, certain plants can produce substances that stimulate the growth of microorganisms or reduce the toxicity of xenobiotics.
Rhizofiltration	Rhizofiltration is one of the phytoremediation methods that uses plants to clean the contaminated soil environment. In this process, the root system of plants participates in the process of cleansing from xenobiotics. As a result of rhizofiltration, pollutants are removed from the soil, or the latter acquire less toxic forms. This process is effective in removing a variety of xenobiotics, including petroleum products, heavy metals, and other organic and inorganic substances.
Phytovolatilisation	Phytovolatilisation is an effective method of soil phytoremediation that uses plants to clean the contaminated soil environment. In this process, plants are used to extract and transform xenobiotics by binding them and volatilising them into the air. The process of phytolatilisation involves phytovolatilisers – plants that can absorb organic substances through the root system and release them in the form of evaporation through leaves or stems (foliar). They are further decomposed by atmospheric processes to less toxic compounds. Phytovolatilisation is an effective method of cleaning soils from xenobiotic contaminants such as petroleum products, organochlorine compounds, and chemical residues. Phytovolatilisation removes pollutants from the soil and converts them into less toxic forms, which considerably improves the quality of the soil environment. However, this process can be more time-consuming than other herbal remedies and require a long time to achieve noticeable results.

***Table 5.** Continued*

Phytodegradation	Phytodegradation is an important process in soil phytoremediation, which aims to clean contaminated soil environments from toxic compounds using plants. Phytodegradation uses enzymes and other plant mechanisms to break down pollutants into less toxic or harmless compounds. The process of phytodegradation involves various biochemical reactions, such as hydrolysis, oxidation, enzymatic action of dehydrogenase, etc. These reactions are produced by different parts of the plant, such as roots, stems, leaves, and root system microorganisms. Phytodegradation allows toxic pollutants to be degraded into less toxic or even harmless components that are absorbed by plants or removed from the soil. This process is an effective method of soil treatment, using natural decomposition mechanisms to reduce the need for chemicals or artificial processes.

Source: developed by the author of this study based on data from S. Rock *et al*. (2000)

According to the US Environmental Protection Agency's "Introduction to Phytoremediation" report, phytoremediation is a technology that uses the ability of plants to degrade, retain (immobilise) and remove contaminants in soil (Rock *et al.*, 2000). M.N.V. Prasad, a professor at the School of Science, University of Hyderabad, India, has calculated that the cost of cleaning soil contaminated with heavy metals, radionuclides, oil, or pesticides using plants that use only solar energy is only 5% of the cost of other remediation methods. This makes phytoremediation a more environmentally sound and cost-effective method of soil decontamination compared to physical, chemical, and technical methods, even if the time available to achieve the ultimate goal is limited. Phytoremediation processes are based on the ability of plants to accumulate, decompose, stabilise, transform, and volatilise pollutants from various natural environments such as soil and water (Tsytsiura *et al.*, 2022). Notably, plants also have defence mechanisms that regulate the absorption of pollutants. There are several mechanisms to control the supply of ions. They mainly accumulate in the reproductive organs and roots. The study of the movement of pollutants in plants showed that at the first stages of the elements' intake from soils, most of them accumulate in plant roots. It is assumed that the delay occurs at the periphery of the roots. Therewith, with the intensive intake of toxic ions from the soil, the defence mechanisms of the root system cannot fully protect the vegetative mass from pollution, which ultimately leads to the deposition of pollutants in the aerial parts of plants.

The chemical composition of plants depends on the composition of the soil in which they grow. As plants selectively absorb the necessary elements according to their physiological and biochemical needs, the chemical composition of plants does not repeat the chemical composition of the soil. The mechanisms of plant resistance to excess heavy metals are diverse: some plants can manifest tolerance to heavy metals and accumulate high concentrations, while others, by maximising the use of barrier properties, reduce the amount of their intake and translocation. The level of heavy metal accumulation by plants is influenced by their genetic and species characteristics.

The development of phytoremediation methods for soils contaminated as a result of military and anthropogenic impacts used in crop production is of particular importance. This is because xenobiotics present in contaminated soil can move through the soil profile and accumulate in the organs of agricultural plants, including those used for human or animal consumption. The development of scientific methods and approaches to decontamination using phytoremediation of such soils is truly relevant.

Algorithm of Remediation Actions for Agricultural Land

In Ukraine, there is a need to develop cost-effective and environmentally efficient technologies for phytoremediation of agricultural land contaminated by military and anthropogenic factors. The use of phytoremediation technologies will not only reduce the level of environmental pollution by xenobiotics, but also, most importantly, return the restored agricultural land to land use, as heavy metals can transfer from the soil to plants and then to food. The very fact that heavy metals get into food makes it impossible to use land for crop and livestock production, considering the danger to both humans and animals. For instance, the Commission Regulation (EC) No. 1881/2006 (2006) sets maximum levels of certain contaminants in food. The restriction in the regulation also applies to heavy metals.

In terms of the agricultural lands of Ukraine affected by military operations, it is proposed to use a generalised algorithm aimed at soil restoration using phytoremediation as one of the possible methods. Simplified algorithm of actions for agricultural land damaged by explosions, burning of military equipment and ingress of fuels and lubricants into the soil:

1. demining of designated areas;
2. satellite monitoring of areas with the creation of a soil pollution map;
3. soil sampling in and around the explosive impact zone;
4. laboratory analysis for heavy metals, toxins, and other pollutants;
5. analysis of further land use and agricultural opportunities;
6. mechanical cleaning of contaminated areas from debris, sources of pollution, and remnants of hostilities;
7. Mechanical restoration of soil cover in areas damaged by explosions;
8. development of a phytoremediation plan and determination of the best phytoremediant;
9. step-by-step monitoring of phytoremediation results through soil sampling and analysis;
10. decision-making on returning the restored areas to agricultural production.

Thus, the stages of soil cleanup on land affected by military operations include the identification and assessment of the degree of contamination, mechanical removal of hazardous material residues, selection of a phytoremediant, monitoring and evaluation of the results with adjustment of the method, if necessary, and the final assessment of the degree of readiness of the soil to return to agricultural production. Notably, herbal mediation is a lengthy process that requires investment to intensify, and therefore economic substantiation to ensure the best possible result is a significant component.

Conclusions

Phytoremediation is a vital and promising area for restoring soil quality and preserving the environment. The ability of soils to restore their functional characteristics that have been lost as a result of military and anthropogenic stress depends on their type, the impact of military and anthropogenic factors, and the landscape conditions of the territory. An important mechanism for intensifying soil restoration is the combined impact of soil quality restoration technologies through the introduction of phytoremediation methods and techniques. Considering the landscape and zoning of agricultural land contaminated by military operations, phytoremediation offers a flexible approach to choosing a phytoremediant, which allows for the most suitable approach. In addition, phytoremediation can be combined with conventional soil remediation methods, enhancing their effectiveness.

The military-anthropogenic load on the soil leads to a series of physical, mechanical, and chemical interventions in the soil cover system. These interventions destroy the functions of the soil ecosystem and its structure, which leads to a deterioration in its quality and functional properties. Destruction of vegetation, damage to soil cover, chemical pollution, and insufficient natural moisture are typical consequences of military operations. This considerably impoverishes the biodiversity, which affects species and populations, and the loss of biodiversity changes the function and structure of landscapes. The dynamic nature of the military-anthropogenic load and a wide range of factors affecting the ecosystem require a scientific approach to investigating the problem, and therefore the development of standardised action algorithms that will help improve the efficiency of decontamination of contaminated soils. The prospect of further research, in addition to algorithmisation of decontamination processes, may be to investigate the dynamics of the impact of military-anthropogenic load on the ecosystem and to create more flexible mechanisms for eliminating pollution using artificial intelligence and neural network tools. Considering the initial data, which will accommodate the factors of contamination, its degree, type or combination of types, soil type, and other natural conditions, as well as the desired result, the use of artificial intelligence will allow quickly creating a contamination mapping, decontamination forecast, determining the most suitable remediation agent and action algorithm. The synergy of this approach with technologies, such as remote monitoring using unmanned systems, would allow, apart from regular monitoring of pollution zones, to create maps of areas where herbal remedies are used, track the dynamics of their growth, condition, etc. The availability of a wide range of phytoremediation crops and a fairly typical set of xenobiotics of military-anthropogenic origin allows creating systematic and standardised algorithms for soil remediation, which helps to increase the efficiency of soil restoration.

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Conflict of Interest

The author of this study declares no conflict of interest.

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Фіторемедіація ґрунтів, забруднених внаслідок військово-техногенного навантаження

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Анотація. Військові конфлікти та техногенні аварії спричиняють значне забруднення ґрунтів важкими металами, нафтовими продуктами, пестицидами та іншими токсичними речовинами. Метою даної статті було висвітлення факторів впливу воєнно-техногенного навантаження на ґрунти та аналіз наявних методик щодо їх ремедіації. Узагальннено існуючі та перспективні методики фіторемедіації з оцінкою їх впливу на забруднення ґрунтів хімічними речовинами, які є типовими забруднювачами під час військових конфліктів. В результаті проведеного дослідження було підсумовано, класифіковано та порівняно групи забруднювачів, які є найбільш поширеними під час воєнних дій; проаналізовано вплив забруднювачів на родючий шар ґрунту та їх рухомість; проведено аналіз наявних методів ремедіації. Було встановлено, що наявні технології ремедіації ґрунтів, які можуть бути застосовані як окремо так і в комбінації, надають необхідний інструментарій для вирішення проблеми хімічного забруднення ґрунтів внаслідок попадання в них токсичних продуктів – похідних вибухових речовин та важких металів. Враховано ступінь економічної доцільності, що відповідно дозволило припустити, що саме фіторемедіація ґрунту може бути найбільш економічно доцільною за певних умов. Це відкриває широкі можливосі щодо наступних досліджень, де застосування синергії екології, економіки та агробіології надасть змогу розробити механізми оптимізації методів фіторемедіації ґрунтів з врахуванням їх типу, профілю та цільовому призначенню. Запропоновано алгоритм дій щодо ремедіації ґрунтів внаслідок військово-техногенного навантаження, який включає в себе пов'язаний комплекс супутніх дій з зонування, розмінування, оцінки та повернення земель у промислове використання. Результати дослідження можна застосувати при очищенні промислових територій, що зазнали забруднення під час виробничих процесів або аварій

Ключові слова: ремедіація ґрунту; фіторемедіанти; техногенний вплив; деградація ґрунтів; хімічне забруднення ґрунтів; енергоємні речовини; пропеленти