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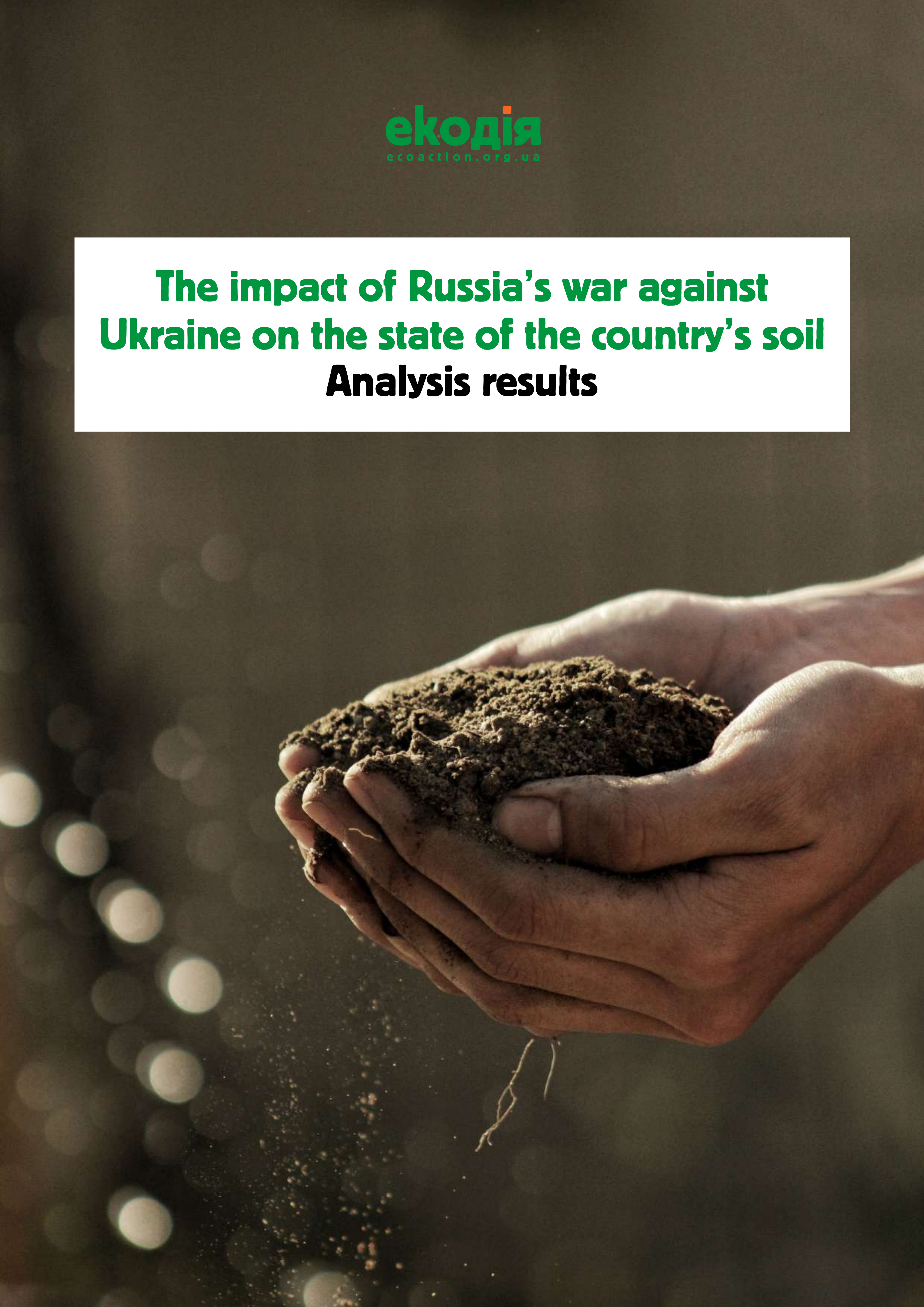
The impact of Russia's war against Ukraine on the state of the country's soil

Analysis results



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CONTENTS

Introduction

Since 2014, Russia's war against Ukraine has dramatically disrupted the soil environment and caused large-scale and long-term environmental degradation. The full-scale invasion since 24 February 2022 has further aggravated the problem of soil degradation and had a significant impact on productivity. Moreover, the high intensity of fighting in certain areas has called into question the safety of using land directly affected by the military action.

Eruptions from aerial bombs and artillery shelling, mined territories, destroyed heavy military equipment, leakage of oil products, burned areas from fires, and landslides have become the main markers signalling a powerful impact on soil resistance to pollution, bringing with it severe socio-economic consequences, both locally and nationally.

This drastic change of landscape requires an immediate and comprehensive study, followed by the development of policies for the management of lands contaminated by war. Failure to act on the identified problem risks causing accelerated soil erosion, adversely affecting production, spreading toxic and contaminated agricultural or other products, and harming human health.

However, monitoring of soil condition assessment is still fragmentary. As such, this study aims to research the impact of military operations on soil by assessing its ecological and geochemical state in areas of active hostilities to determine the criteria for soil pollution according to the degree of damage. Based on its findings, the study also seeks to propose the main measures for post-war restoration of the soil in Ukraine, taking into account the regional landscape and geochemical features and types of land use.

Using mainly geographic information systems (GIS), the key research sites for the study were the Vilkhivka community of the Kharkiv region and the Sartana community of the Donetsk region. Satellite images were taken of the Vilkhivka community in April and May 2022 and of the Sartana community in March 2022. The study also employed laboratory analyses of the physico-chemical condition of soil in the studied areas and examined the results of analyses for the Chernobyl Biosphere Reserve and the Anti-Terrorist Operation (ATO)/ Joint Forces Operation (JFO) zone in the period before the full-scale invasion.

The recommendations made by the study highlight the decision to develop a policy for the post-war restoration of Ukraine's land and bring its ecological condition to a level that is safe for the environment and human health. The given recommendations will be important not only for the national government and relevant ministries, but also for local self-government bodies that are in the zone of active hostilities.

Classification and Description of Soil Pollution in Post-War Landscapes

The consequences of military action for the soil environment are often underestimated when compared with the loss of human lives and infrastructure facilities, however, the deterioration of the quality properties of the soil is long term, which significantly reduces its productive functions. Nevertheless, soil can restore its functional properties and increase productivity interdependently in time depending on the type of soil, the type of military-technogenic impact, and the landscape conditions of the territory.

The evaluation of the military-technogenic load on the soil of post-war landscapes is thus carried out according to the levels of the intensity of military operations, taking into account the types of military pollution. Since 24 February 2022, full-scale military operations in Ukraine have caused disruptions of the soil cover.

These disruptions are conditionally divided into two groups:

- Primary — direct mechanical deformations of the soil cover, thermal pollution; cluttering the surface;
- Secondary — caused by the consequences of failure to implement post-war reconstruction measures such as flooding, salinisation, erosion processes, pyrogenic degradation, and dehumidification.

The mechanical, physical, and chemical impacts on the soil cover caused by military actions lead to the destruction of the structure and functions of the soil ecosystem and the deterioration of physical and geochemical properties, including destruction of vegetation, disruption of the soil cover, lack of natural moisture, and desertification. As a result, the level of biodiversity is sharply reduced, which in turn affects biological populations and species. The loss of biodiversity is further exacerbated by changes in the structure and functions of landscapes.

Mechanical impact and consequences for soil

The mechanical impact during the military-technogenic load is represented by the mechanical deformation of the soil cover during the movement of wheeled and tracked military equipment, direct movement of troops, construction of near-surface and underground structures, bombardment, de-mining of territories, and construction of defence infrastructure.

The main mechanical impact on the soil is **compaction with damage to the humus layer,** which has direct negative consequences, such as disturbing the water balance of the soil, and causes the development of wind and water erosion. This destruction of the soil structure occurs as a result of the displacement of the particles of one layer with respect to another under the action of military-technogenic load, worsening the adaptation of plants to climate changes, arid conditions, and lack of moisture[1]. At the same time, the soil becomes more resistant to further military-technogenic impacts in conditions of constant lack of productive moisture.

[1] Балюк С.А., Медведєв В.В., Воротинцева Л.І., Шимель В.В. Сучасні проблеми деградації ґрунтів і заходи щодо досягнення нейтрального її рівня. Вісник аграрної науки. 2017. № 8. С. 5-11

Meanwhile, the formation of near-surface and underground **fortification structures** (dungeons, trenches, tunnels, and storage facilities for fuel, lubricating materials, and combat equipment) leads to deformations of the soil cover. This increases a number of dangerous geomorphological processes, such as landslides, water-logging, and soil subsidence, which is why it is important to take into account the depth of groundwater and soil moisture conditions during the construction of these fortification structures.

The formation of **craters** on the other hand is caused by bombing during hostilities, the explosive action of which causes rapid release of energy, which forms a circular shock wave surrounding the point of impact that is the funnel. After the explosion, the soil is partially removed, forming a pit. This type of soil disturbance is defined as **bombturbation[2].**


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During this process, the explosive wave provokes the destruction of the sequence of soil horizons, which leads to a disruption of the air-water regime. The largest products of the explosion remain at the bottom of the crater or mostly tightly adhere to it, along with the accumulation of water and organic matter. Hydrophilic vegetation, which is different from the typical vegetation cover of the area, and which indicates increased soil moisture, soon forms at the bottom of the explosion crater or funnel. If craters are formed in places with a groundwater level close to the surface, soil development and plant vegetation slow down.

The **de-mining** of territories has equally negative impacts, as the humus horizon is destroyed, the physico-chemical properties of the soil are lost, and the granulometric and aggregate state changes, subsequently affecting the potential fertility and water-holding capacity of the soil. The installation of mines in itself predicts soil turbulence in the future. Detonation contaminates the soil with metal fragments and explosive residues[3] while landmine clearance operations are often complex and expensive. As such, in developing countries, these consequences can be interpreted as an absolute loss of soil resources.

However, the primary consequence of the military-technogenic load is the **occurrence of fires.** As a result of the removal of humus substances and the formation of a hydrophobic layer on burnt areas, which limits the penetration of water, these provoke processes of water and wind erosion in the future.

[2] Hupy, J.P., Schaetzl, R.J., 2006. Introducing "bombturbation", a singular type of soil disturbance and mixing. Soil Sci. 171, 823–836.

[3] Takahashi, K., Preetz, H., Igel, J., 2011. Soil properties and performance of landmine detection by metal detector and ground-penetrating radar — soil characterisation and its verification by a field test. J. Appl. Geophys. 73, 368–377.

Physical impact and consequences for soils

Physical impact should be understood as a change in the physical properties of the soil cover as a result of the use of weapon systems and military equipment. The main manifestations of physical soil pollution are vibration, radioactive, and thermal impacts.

The vibration impact is associated with the generation of energy pulses during military operations and is characterised by lower vibration frequencies and their transmission through solid objects that are in direct contact with mechanisms that are effective. Single impulses arise from the explosions of ammunition on target fields and from firing various weapons systems, while periodically repeated ones are noise and vibration from the operation of military equipment. The vibration transmitted in the soil can lead to its compaction, squeezing out of water, subsidence of the surface, formation of cavities, and changes in the microrelief.

Radioactive impact is caused by an increase in the content of radioactive substances due to the use of ammunition with depleted uranium, and devices with sources of ionising radiation. Currently, the use of this type of weapon has not been reported in Ukraine.

Thermal impact causes a local increase in temperature due to emissions of heated air, powder gases, gaseous products, and exhaust gases. The thermal impact has a negative effect on the soil cover, causing a disruption of the thermal and water regime and changes in the granulometric and aggregate composition. A change in the thermal regime of the soil affects soil organisms, changing their level of oxygen saturation, which results in a decrease in biodiversity.

Chemical impact and consequences for soil

The chemical impact of military activities leads to a change in the natural parameters of the soil cover under the influence of pollutants produced as a result of the use of weapon systems and military equipment. Long-term military activity causes the formation of local military-technogenic geochemical anomalies with a different spectrum of explosive and other toxic substances, which can impose an indefinite ban on the use of land.

Chemical pollution of war-made origin includes vehicle fuel, lubricants, solvents, electroplating waste, residues of explosives, decontamination substances, heavy metals and their compounds, and radioactive substances. Dangerous substances of the physico-chemical type are explosive materials.

During firing, **ammunition** with different composition of gunpowder and explosives is used, the combustion of which produces substances such as nitrogen, soot, hydrocarbons, lead, manganese dioxide, and other derivatives, which negatively affect human health and the natural environment. For example, during the explosion of one 115 mm high-explosive munition equipped with hexane, about 4,000 litres of gas is formed, which contains the combustion products of this explosive substance. Up to 30% of gases are dispersed in the air, and most of them (heavy fractions and heavy metals) settle on the soil[4,5].

Explosives also play a significant role in the release of metals into the soil environment. Particles ejected from artillery strikes have been found to contain high levels of lead (Pb) and copper (Cu)[6]. Explosive grenades were also considered a significant source of high concentrations of lead (Pb)[7].

[4] Cherp O.M., Vinnychenko V.N., Khotuleva M.V. Molchanova Ya.P., Dayman S.Yu. Ecological evaluation and expertise.- Moscow, Ecoline, 2000, URL: http://www.ecoline.ru/mc/books/, 202 p. (in Russian)

[5] Peregudov F.I., Tarasenko F.P. Introduction in system analysis. – Moscow, Vystshaya Shlola, 1989.- 367 p. (in Russian)

[6] Gillies, J.A., Kuhns, H., Engelbrecht, J.P., Uppapalli, S., Etyemezian, V., Nikolich, G., 2007. Particulate emissions from U.S. Department of Defense artillery backblast testing. J. Air Waste Manag. Assoc. 57 (5), 551–560. https://doi.org/10.3155/1047-3289.57.5.551

[7] Weber, A.K., Bannon, D.I., Abraham, J.H., Seymour, R.B., Passman, P.H., Lilley, P.H., Parks, K.K., Braybrooke, G., Cook, N.D., Belden, A.L., 2020. Reduction in lead exposures with lead-free ammunition in an advanced urban assault course. J. Occup. Environ. Hyg. 17 (11–12), 598–610. https://doi.org/10.1080/ 15459624.2020.1836375

Unexploded ordnance and landmines have been causing serious damage to the soil in Ukraine for decades due to the release of toxic substances resulting from corrosion of ammunition. Furthermore, the risks associated with accidental detonation[8] as well as landmine contamination poses a serious threat to local communities and deprives them of access to land and natural resources.

Heavy metals are another major pollutant of soil. According to preliminary studies of the ATO/JFO zone during 2016-2020, a high content of lead, copper, arsenic, zinc, chromium, cadmium, molybdenum, barium, potassium, magnesium, and tungsten[9] was found in the soil. These elements characterise the dominant spectrum of military-technogenic pollution and are leading indicators for forecasting changes in the ecological state of territories with contaminated soil and the territories adjacent to them.

Meanwhile, in places where **fuel and lubricants** are spilled, changes in the chemical composition of the soil result in the disruption of one of its most important properties of the soil — the ability to self-recover — and the decreasing of its biological activity.

Finally, **hydrocarbon-contaminated** soil is a source of airborne toxic gases and dusts that have acute impact on soil biodiversity[10]. While benzene, toluene, ethylbenzene, and xylene released from freshly contaminated soils can cause chronic effects on public health. After entering the soil, hydrocarbons can completely or partially occupy the pore space of the soil, blocking the flow of air and water. This affects the respiration of plant roots and soil microorganisms, as well as the supply of these biota with moisture[11].

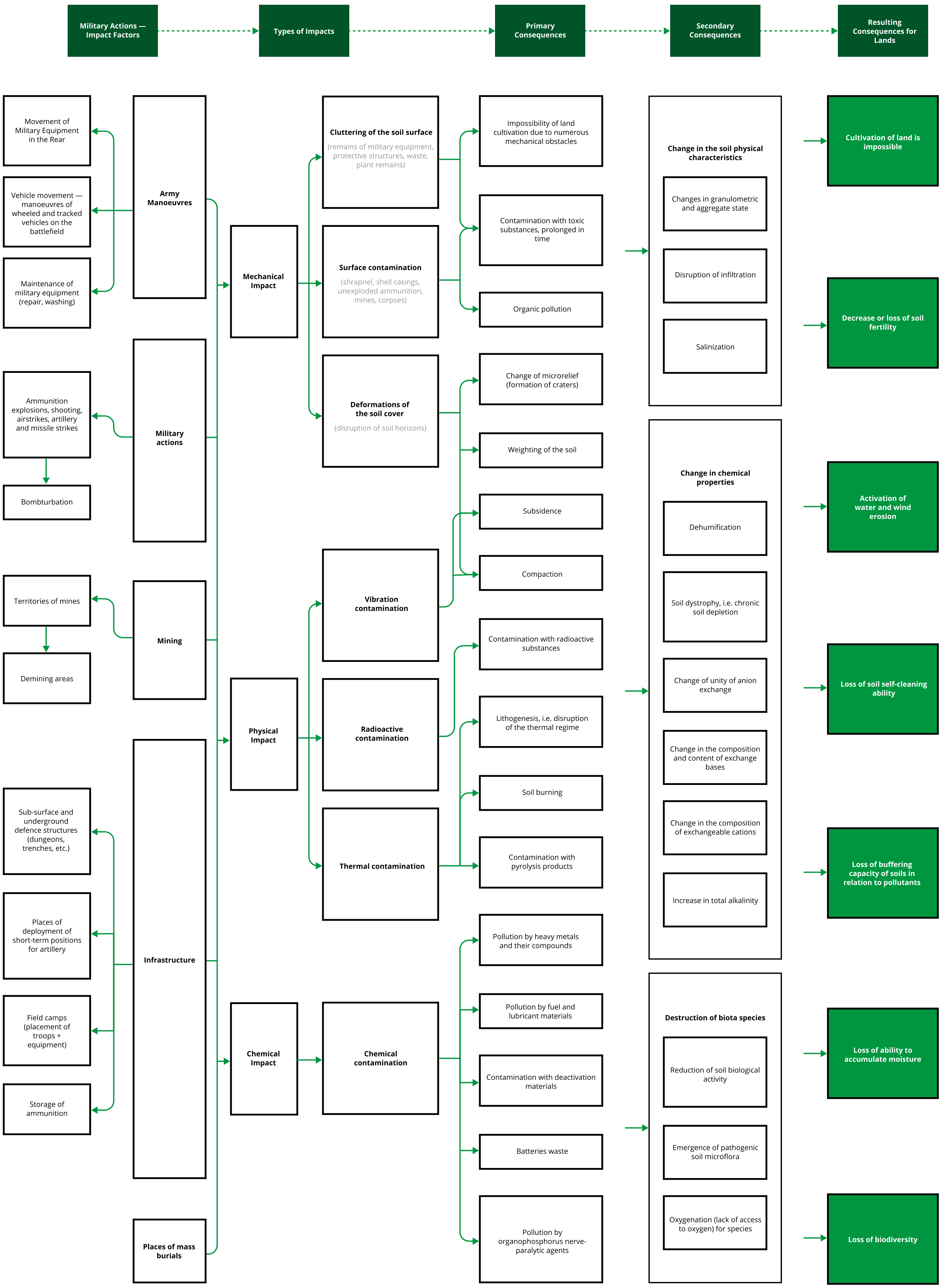
The composition and interrelationship of war-made factors impacting the soil is presented in Scheme 1.

[8] Dimitrios Kalderis, Albert L. Juhasz, Raj Boopathy, and Steve Comfort. Soils contaminated with explosives: Environmental fate and evaluation of state-ofthe- art remediation processes (IUPAC Technical Report) Pure Appl. Chem., Vol. 83, No. 7, pp. 1407–1484, 2011. doi:10.1351/PAC-REP-10-01-05

[9] Прикладне ландшафтознавство : історія, сучасність, перспективи: матеріали Всеукраїнського наукового семінару пам'яті професора Анатолія Мельника (Львів – Ворохта, 6-9 жовтня 2022 року). – Львів : ЛНУ ім. Івана Франка, 2022. – 55 с.

[10] Meng, C., Li, M., Li, Q., Hu, Y., Li, Y., 2018. Characterizing the spatio-temporal exposure and health risks of polycyclic aromatic hydrocarbons in an oilfield, China. Hum. Ecol. Risk Assess. 24 (4), 971-990.

[11] Khan, K.Y., Ali, B., Stoffella, P.J., Feng, Y., Cui, X., Guo, Y„ Yang, X., 2020. Bioavailability and bioaccessibility of Cd in low and high Cd uptake affinity cultivais of Brassica rapa ssp. Chinensis L. (Pakchoi) using an In vitro gastrointestinal and physiologically-based extraction test. Commun. Soil Sci. Plan 51 (1), 28-37.



Scheme 1. *Tools for detecting types of soil disruptions and establishing the subordination of disruptions to the main war-made factors of impact*

Military-technogenic impact on soil and consequences for human health

Military-technogenic (war-made) impacts cause specific contamination of the soil environment. Along with emissions of organic pollutants, military activities are closely related to soil contamination with heavy metals[12]. Consequently, emissions of pollutants associated with military activities can indicate a direct impact on the environment and **play a significant role in the health of the civilian population.** Exposure to war-made pollutants has been shown to cause adverse health effects related to cardiovascular, metabolic, neurological, and oncological diseases[13].

A number of studies separately testify to the **adverse consequences** of military-technogenic impact **on the health of children** living in the territories of hostilities. For example, stunted growth and neurological development in children were associated with in utero exposure to heavy metals, primarily arsenic, barium, and molybdenum[14]. Similarly, an increase in the number of pre-term births and the prevalence of birth defects in newborns in the Gaza area (Palestine) is due to increased exposure of the female population to high levels of barium, arsenic, cobalt, cadmium, chromium, vanadium, and uranium[15]; while children in the war zone of Iraq have been found to have impaired neurological development[16].

The entry of pollutants into the human body is also a risk factor for the development of various pathologies and the growth and complication of the course of a number of diseases. Many micro elements, including those necessary for living organisms, in abnormally high concentrations are toxic to humans[17,18]; with even small concentrations of pollutants changing the activity of enzymes in the human body, affecting the blood circulation of nuclei and protein synthesis and **causing changes at the genetic level[19].**

After entering the soil, the "behaviour" of explosive compounds and heavy metals is influenced by various natural processes[20,21]. The speed of their migration and transformation is regulated by physico-chemical and biological factors of the soil environment (such as dissolution, evaporation, adsorption, photolysis, hydrolysis, and biodegradation). The mobility of pollutants in the soil environment depends on the granulometric and mineralogical composition of the soil, humus content, redox and acid-alkaline conditions, and the presence of geochemical barriers.

Moreover, the time aspect has a great influence on the behaviour of pollutants. For instance, soluble organic substances and acidification of the soil environment increase the rate of pollutant migration.

[12] Neffe, S., 1998. Chemical aspects of environmental contamination at military sites. Environmental Contamination and Remediation Practices at Former and Present Military Bases. Springer, Dordrecht, pp. 83–92.

[13] Rehman, K., Fatima, F., Waheed, I., Akash, M.S.H., 2018. Prevalence of exposure of heavy metals and their impact on health consequences. J. Cell. Biochem. 119 (1), 157–184. https://doi.org/10.1002/jcb.26234

[14] Baraquoni, N.A., Qouta, S.R., VЁanskЁa, M., Diab, S.Y., PunamЁaki, R.L., Manduca, P., 2020. It takes time to unravel the ecology of war in Gaza, Palestine: long-term changes in maternal, newborn and toddlers' heavy metal loads, and infant and toddler developmental milestones in the aftermath of the 2014 military attacks. Int. J. Environ. Res. Publ. Health 17 (18), 6698. https://doi.org/10.3390/ijerph17186698

[15] Manduca, P., Al Baraquni, N., Parodi, S., 2020. Long term risks to neonatal health from exposure to war-9 Years long survey of reproductive health and contamination by weapon-delivered heavy metals in Gaza, Palestine. Int. J. Environ. Res. Publ. Health 17 (7), 2538. https://doi.org/10.3390/ijerph17072538

[16] Savabieasfahani, M., Alaani, S., Tafash, M., Dastgiri, S., Al-Sabbak, M., 2015. Elevated titanium levels in Iraqi children with neurodevelopmental disorders echo findings in occupation soldiers. Environ. Monit. Assess. 187 (1), 4127. https://doi.org/10.1007/ s10661-014-4127-5

[17] Бардик Ю. В. Еколого-гігієнічні та токсикологічні проблеми життєдіяльності / Ю. В. Бардик, О. О. Бобильова // Сучасні проблеми токсикології. – 2005. – № 4. – С. 33-36.

[18] Вадзюк С. Н. Медико-екологічні проблеми в сучасних умовах / С. Н. Вадзюк, О. Є. Федорців // Збалансований розвиток країни – шлях до здоров'я і добробуту нації: матеріали Українського екологічного конгресу, 21 вер. 2007 р. – К.: Центр екологічної освіти та інформації, 2007. – С. 41-44.

[19] Chapman, G.; Yudken, J. Briefing book on the miltary industrial complex. Council for a livable world education fund, Washington DC, 2000. 543 p.

[20] J. C. Pennington, J. M. Brannon. Thermochim. Acta 384, 163 (2002).

[21] A. L. Juhasz, R. Naidu. Rev. Environ. Contam. Toxicol. 191, 163 (2007).

The redistribution of pollutants occurs both horizontally and vertically:

- **horizontal migration** is most noticeable immediately after the bombings and occurs primarily due to air transportation;
- **vertical migration** is associated with the diffusion of ions, transfer with moisture flow, transfer by root systems of plants, activity of soil mesofauna, and human economic activity.

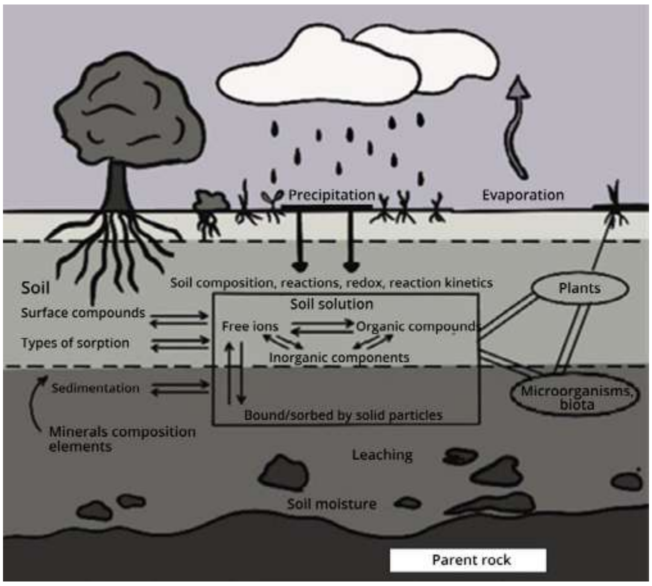
The greatest impact on the intensity of pollutant migration in the soil profile is exerted by the water regime[22]. The ability of soils or groundwater to retain heavy metals by selective absorption (adsorption) also depends on the surface area that reacts with the metal. The intensity of fixation of heavy metals depends on the composition of the soil-forming rock as well, which differs in the content of clay and organic matter, humidity, rate of gas exchange with the atmosphere, microbiological activity, and other landscape-geochemical factors[23].

The presence of **vegetation** in the areas of war-made load also affects the mobility of explosives and heavy metals. For example, plants have the ability to reduce their migration to groundwater[24]. For this reason, perennial grasses such as miscanthus and wood species such as willows *(Salix sp.)* and poplars *(Populus sp.)* are often used[25].

Several factors affect the uptake of heavy metals by plants from the soil: species characteristics of plants, soil type, concentration, form of presence of polluting elements, soil pH, granulometric composition, content of organic substances, absorption capacity of cations in the soil, and presence of man-made sources of landscape pollution.

At the same time, **plants have protective properties** regarding the absorption of pollutants. They have several systems for controlling the flow of ions, for instance, which are mostly found in roots and reproductive organs (seeds and fruits). The study of the migration of pollutant elements in plants has proved that at the first stages of the entry of elements from the soil, their main part is retained in the roots of plants (Scheme 2). Even so, the protective mechanisms of the root system are limited, and during the intensive influx of toxic ions from the soil, they are unable to fully protect the vegetative mass from pollution, and polluting elements begin to penetrate into the aerial part of plants.

The chemical composition of plants depends on the composition of the soil in which they grow, but does not repeat it, since they selectively absorb the necessary elements in accordance with physiological and biochemical needs. Mechanisms of resistance of plants to excessive intake of heavy metals are diverse: some are able to accumulate high concentrations of metals and show tolerance to them, others can reduce their intake by making maximum use of barrier properties. The level of accumulation of heavy metals by plants thus depends on their genetic and species characteristics[26].



Scheme 2. *Processes of pollutant migration in soils*

[22] Драган Н.А. Мониторинг и охрана почв. Учебное пособие. – Симферополь: Изд-во ТНУ, 2008. с. 172

[23] Billett M.F., Fitzpatrick E.H., Crisser M.S. Long-term changes in the Cu, Pb and Zn content of forest soil organic horizons from North-east Scotland. Water, Air and Soil pollution, 1991, V. 59, N1-2, c.179-191.

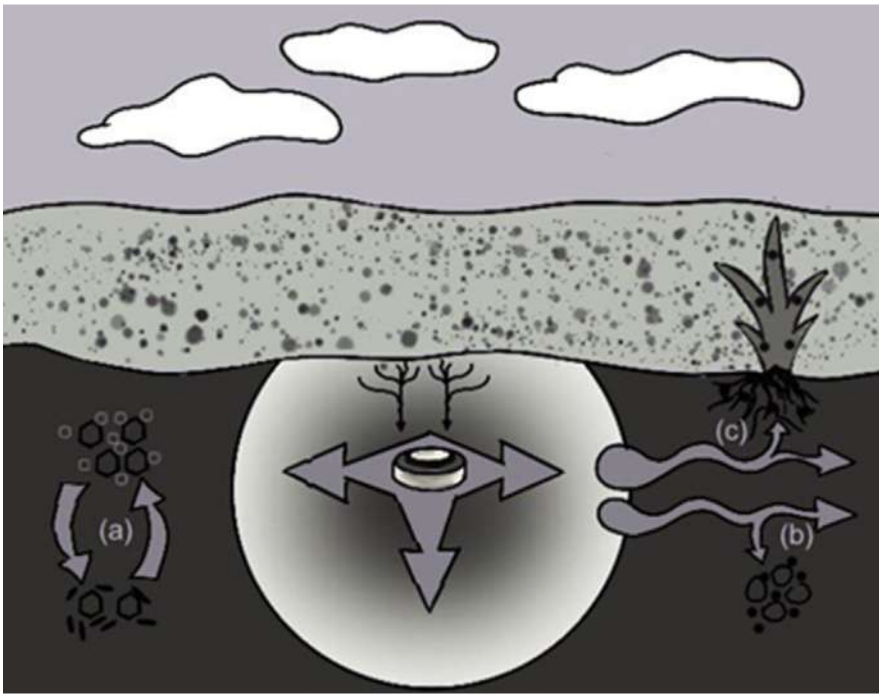
[24] Fayiga, A.O., 2019. Remediation of inorganic and organic contaminants in military ranges. Environ. Chem. 16 (2), 81-91.

[25] Rylott, E.L., Bruce, N.C., 2019. Right on target: using plants and microbes to remediate explosives. Int. J. Phytoremediation 21 (11), 1051-1064.

[26] Сорокина Л.Ю., Сплодитель А.О. Распределение тяжелых металлов в системе «почва-растение» в ландшафтах территории Национального природного парка «Нижнесульский». «Могилевский меридиан». 2017. Т.17, вып. 3-4(39-40). С. 19-24

Among agricultural crops, the highest content of heavy metals was found in leafy vegetables and silage crops, and the lowest in leguminous, cereal, and technical crops[27].

War-made pollutants are usually present in the soil in the form of residues or particles from the use of munitions and enter the soil by dispersion. These pollutant compounds have different levels of solubility in water and a high degree of penetration into the transition layers of the soil. However, for the most part, these compounds have high concentrations in the near-surface layer of the soil (up to 15 cm). Upon release, explosive compounds come into contact with the soil, where they are absorbed and adsorbed by its particles (Scheme 3). The duration of sorption depends on the structure of compounds[28].



Scheme 3. *Behaviour of explosive substances compounds in soils**

**Note. The central icon represents unexploded ordnance, and the colour behind it represents contamination diffusion. Water is indicated by light arrows, and the presence of pollutants outside the central diffusion zone is indicated by cultivated hexagons. Area (A) represents microbial interaction and metabolism, area (B) represents sorption by soil particles, and area (C) is for uptake and sequestration by aerial and below ground plant tissues[29].*

A strategy **plant-pollutant** interaction begins with uptake of the pollutant and usually occurs through a liquid solution present in the porous soil matrix. The soil solution containing the explosive compounds penetrates the plant roots if there are no obstacles and through the large flow of water during evaporation[30]. Compounds of explosive substances inside the roots then move freely between the membranes, and, in the end, completely settle in the plant[31,32]. Some studies indicate the accumulation of potentially toxic levels of Pb, Cu, and Ni in forage plants growing on former military training grounds in Switzerland[33] and in certain areas of Kosovo that were heavily bombarded with depleted uranium shells, which are still characterised by increased accumulation of uranium in lichens[34].

[27] Панин М.С. Контроль уровня загрязненности тяжелыми металлами сельскохозяйственной продукции / М.С. Панин // Докл. третьей междунар. науч.-техн. конф. Пища. Экология. Человек. – М., 1999. – С. 126

[28] J. C. Pennington, J. M. Brannon. Thermochim. Acta 384, 163 (2002).

[29] Via S.M. (2020) Phytoremediation of Explosives. In: Shmaefsky B. (eds) Phytoremediation. Concepts and Strategies in Plant Sciences. Springer, Cham. https://doi.org/10.1007/978-3-030-00099-8_8

[30] Singh, S.N., Mishra, S., 2014. Phytoremediation of TNT and RDX. In: Singh, S.N. (Ed.), Biological remediation of explosive residues. Springer, Cham, pp. 371–392.

[31] Ghosh, M., Singh, S., 2005. A review on phytoremediation of heavy metals and utilization of its by-products. Appl. Ecol. Environ. Res 3, 1–18.

[32] Pilon-Smits, E.A., 2005. Phytoremediation. Annu. Rev. Plant. Biol. 56, 15–39.

[33] Robinson, B.H., Bischofberger, S., Stoll, A., Schroer, D., Furrer, G., Roulier, S., Gruenwald, A., Attinger, W., Schulin, R., 2008. Plant uptake of trace elements on a Swiss military shooting range: uptake pathways and land management implications. Environ. Pollut. 153 (3), 668–676. https://doi.org/10.1016/j.envpol.2007.08.034

[34] Di Lella, LA., Fran, L, Loppi, S., Protano, G., Riccobono, F., 2003. Lichens as of uranium and other trace elements in an area of Kosovo heavily with depleted uranium rounds. Atmos. Environ. 37 (38), 5445-5449

Similarly, both TNT and its transformation products are highly toxic to soil fauna, although species show varying susceptibility to these pollutants. Exposure to TNT and other chemical munitions can dramatically suppress soil microbial activity[35], while high concentrations of hydrocarbons can cause symptoms of poisoning in earthworms.

Besides migration in soils, toxic substances are also able to disperse in water. For example, dangerously high levels of explosive compounds leached from munitions, as well as numerous toxic substances from the use of various weapons systems during military exercises, have been found in coastal areas of Puerto Rico. Recent studies of the trace element composition of marine and terrestrial plants in this region[36,37] revealed high concentrations of lead. This indicates the dispersion of pollution and **bioaccumulation of toxic substances in the marine food chain.**

Despite the fact that there are currently only a few studies of military-technogenic impacts, there is indisputable evidence of their adverse consequences for the health of the population. The effect of high concentrations of heavy metals on the human body leads to damage or changes in the activity of the most important systems of the body, that is, the central and peripheral nervous system, haematopoiesis, and internal secretion, among others[38]. In addition, a number of chemical elements cause the occurrence of atherosclerosis and malignant neoplasms, and affect the heredity apparatus. It for this reason that epidemiological monitoring is an important component of a comprehensive programme of research into the territories of war-made impacts.

[35] Gong, P., Hawari, J., Thiboutot, S., Ampleman, G., Sunahara, G.I., 2001. Ecotoxicological effects of hexahydro-1,3,5-trinitro-1,3,5-triazine on soil microbial activities. Environ. Toxicol. Chem. 20, 947–951.

[36] Diaz E, Massol-Deya A (2003) Trace element composition in forage samples from a military target range, three agricultural areas, and one natural area in Puerto Rico. Caribb J Sci 39:215–220

[37] Massol-Deya A, Perez D, Perez E, Berrios M, Diaz E (2005) Trace elements analysis in forage samples from a US Navy bombing range (Vieques, Puerto Rico). Int J Environ Res Public Health 2:263– 266

[38] Шевченко В.А. Медико-географическое картографирование территории Украины – К.: Наук. думка, 1994. – 158 с.

Examples of assessment of damaged land at the regional and local levels

Regional Level: Donbas

The Donetsk economic district (Donbas), which includes the Luhansk and Donetsk regions, traditionally belonged to the most developed industrial regions of Ukraine. Even in Soviet times, the ecological state of Donbas was assessed as one in crisis, and the area was considered to be part of the emergency ecological zone[39,40]. The liquidation of mines within the restructuring of the coal industry caused irreversible changes in Donbas, which, along with the loss of productive land as a result of the development of industrial buildings, which in turn causes a high level of pollution and soil degradation, is an extremely acute problem for the ecological state.

In addition, the war that has been going on in these territories since 2014 has caused new environmental threats, with the contrast of anomalies of war-made origin increasing sharply within industrial agglomerations and superimposing on the man-made pollution already present there. The greatest war-made load on landscapes is characteristic of the Luhansk (North Luhansk), Sievierodonetsk-Lysychansk, and Toretsk-Horlivka-Yenakiieve industrial agglomerations. These areas were characterised by a significant increase in the level of mercury, arsenic, and cadmium in the soil, which exceeded the maximum permissible concentrations and background values. Soil samples also showed elevated levels of copper, zinc, nickel, lead, strontium, chromium, phosphorus, and barium compared to control sites. The results of analytical studies of the content of heavy metals in the soils of military landscapes, which are simultaneously located in the zones of war-made load and in the zones of influence of industrial facilities, indicate that the regional background values of the content of lead (35-14,000 mg/kg), copper (35-95 mg/kg and 250-330 mg/kg in certain areas), nickel (84-300 mg/kg), and other heavy metals (for example, manganese, chromium and zinc — Mn, Cr, Zn) are exceeded.

By comparing the background values of indicators of the physical and chemical properties of the soils of the industrial agglomerations of Donbas before the start of hostilities, regular changes in the content of certain trace elements and heavy metals were established. The content of heavy metals in soil samples taken at the sites of hostilities mostly exceeded the background value by 3-25 times. A systematic excess of 3-6 times was observed for mercury, vanadium, and cadmium, while in single samples, the background values were exceeded by more than a hundred times. If the average indicators of the gross content of heavy metals in the places of use of small arms, artillery, and rocket bombardments are compared with the background ones for Donbas, then the highest levels of concentrations are noted for cadmium, lead, copper, zinc, and, in some cases, mercury.

Aside from this, the increase in areas of flood and inundation during the rise of groundwater levels leads to an increase in the mobility of man-made elements. Among the highly dangerous elements, zinc has the highest mobility rates, with a content of mobile forms of 10-20% of the gross content. The number of mobile forms of lead in the studied soils of the region reaches 6-8% of the gross content. Chromium has the lowest mobility among the studied hazardous elements — up to 2.2% (Fig. 1).

[39] Yakovliev Y., Chumachenko S. Assessment of ecological hazards in Donbas impacted by the armed conflict in eastern Ukraine. Geneva. Centre for Humanitarian Dialogue. 2017. 60 p

[40] Чумаченко С.М., Яковлєв Є.О. Еколого-техногенні загрози для відновлення Донбасу на засадах збалансованого розвитку. Матеріали конференції Перспективи відновлення Сходу України на засадах збалансованого розвитку. м. Слов'янськ. 2017, С. 24–25.

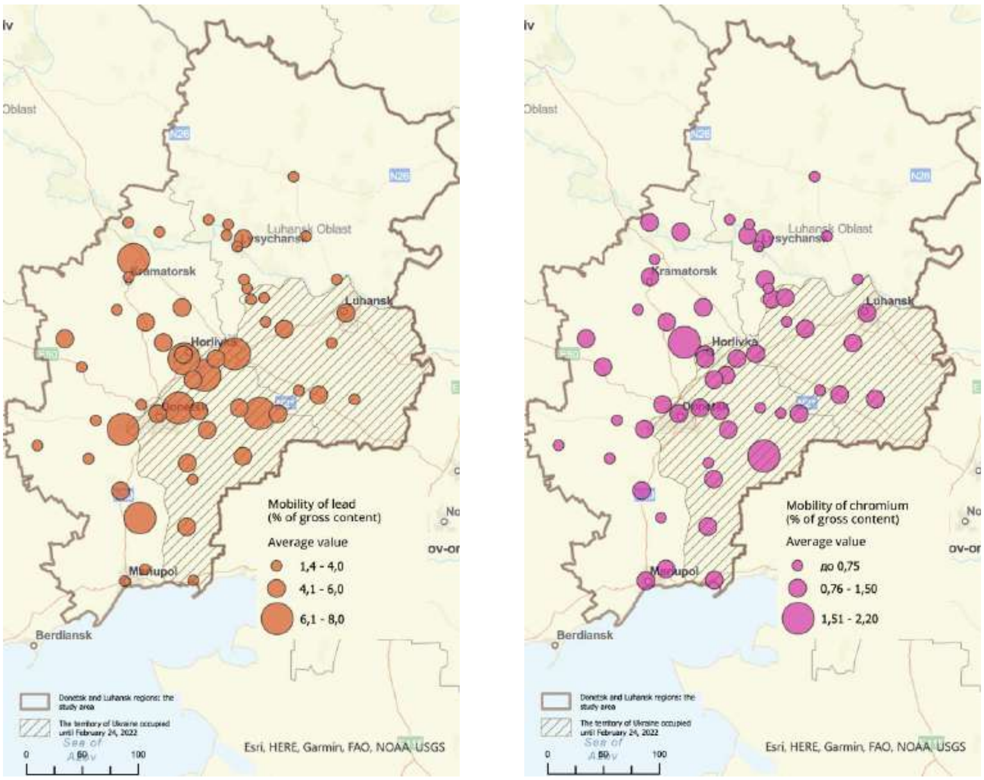


Figure 1. *Distribution of mobile forms of lead (Pb) and chromium (Cr) in the soils of Donbas (2016-2022)*

For soil in war zones, the total pollution index (Zc) was also determined according to the method of Yu. Yu. Saiet (1990). At each soil sampling point, based on the analysis of geochemical samples in accordance with this method, the total indicator of soil chemical contamination was calculated. To calculate Zc, the average background content of chemical elements is taken. The concentration coefficient was calculated for elements with higher background content.

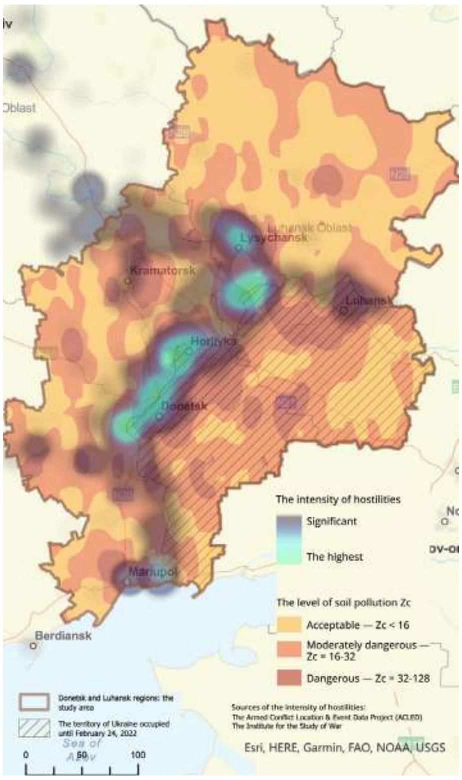


Figure 2. *The level of soil pollution in Donbas with the total pollution index (2016-2022)*

The value of the total indicator of chemical pollution Zc varies in the studied area within wide limits — from 7.3 to 118.5. For instance, calculations of the total indicator of soil pollution proved that the zones of military impact within the region are characterised by dangerous levels of soil pollution with heavy metals (Zc from 32 to 128), while other areas of agglomerations experience a moderately dangerous level of pollution (Zc from 16 to 32). The lowest permissible values of total soil contamination (Zc up to 16) are characteristic of territories with separate habitats located mainly in the northern and north-eastern parts of the region.

Due to significant spatio-temporal changes of natural and man-made factors in the conditions of military impact, the current ecological and geochemical conditions of the soil cover of the Donbas landscapes are extremely complex, which creates high risks of emergency situations of ecological origin. Under the conditions of intense military impact on the landscapes of the region, the level of the background characteristics of the soil cover is increasing, the levels of fluctuations in the concentrations of toxic elements and their compounds are increasing, and the regularities of the processes of forming the chemical composition of the soil are changing.

Local Level: Vilkhivka community (Kharkiv region) and Sartana community (Donetsk region)

The consequences of hostilities on soil were studied in more detail using the example of two key territories — Vilkhivka community in the Kharkiv region and Sartana community in the Donetsk region. These territories were selected for the study since both became the scene of hostilities of varying intensity following the full-scale invasion of the Russian Federation on the territory of Ukraine.

The study of these areas was conducted using GIS in order to:

- Collect and organise initial geospatial data (data on time limits and locations of hostilities, space photographs, basic sets of geodata)*;
- Identify land structure;
- Analyse space images;
- Identify geolocation and characteristics of hostilities — factors of impact on the lands;
- Develop and apply geoprocessing models for analysis of the consequences of hostilities;
- Visualise results on maps.

**Satellite images were taken with WorldView 3[41] with a resolution of 31 cm. The images of the Vilkhivka community were taken in April-May 2022 and of the Sartana community in March 2022. Time limits for space footage that could show the course of hostilities were determined based on the open-source resource The Armed Conflict Location & Event Data Project (ACLED)[42], an institution that specialises in tracking and geolocating conflicts in the world.*

The analysis and assessment of the factors and consequences of hostilities for the land consisted of two main working stages: Identification of land damaged by hostilities; and a comprehensive assessment of the level of damage through a multivariate analysis.

[41] Global enhanced GEOINT delivery [Електронний ресурс] – режим доступу: https://evwhs.digitalglobe.com/myDigitalGlobe/login

[42] The Armed Conflict Location & Event Data Project (ACLED). Ukraine Crisis Hub. https://acleddata.com/ukraine-crisis/

1. Identification of lands damaged by hostilities

First of all, it is worth determining the time limits of hostilities in the studied territories for the selection of high-resolution (<1 m) space images that would make it possible to identify land damage. The use of space images for preliminary assessment of territories is much more effective (saving time and costs) and safer than field survey. However, a field survey is possible to refine the data on the localisation of impacts, which is necessary for the selection of soil samples for laboratory analysis (Fig. 3).

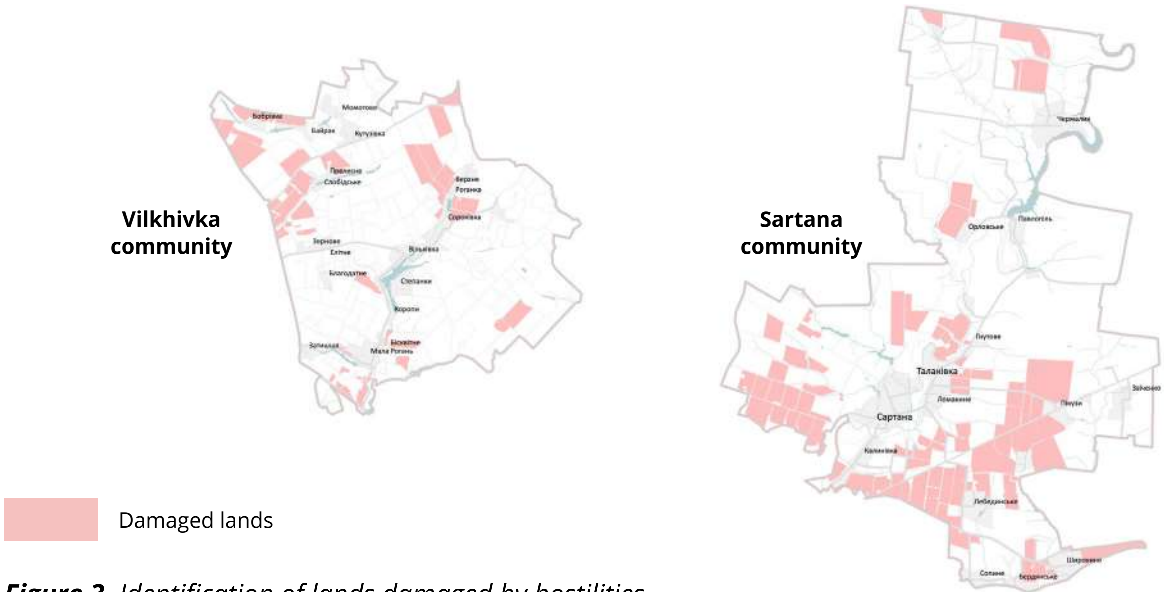


Figure 3. *Identification of lands damaged by hostilities*

Analysis of space images can also determine impact factors (military actions that cause negative consequences for the environment, in particular for soil), including:

- manoeuvres of troops, for example, moving equipment;
- military operations — places of active battles, shelling and explosions;
- infrastructure (fortifications, trenches, positions, etc.).

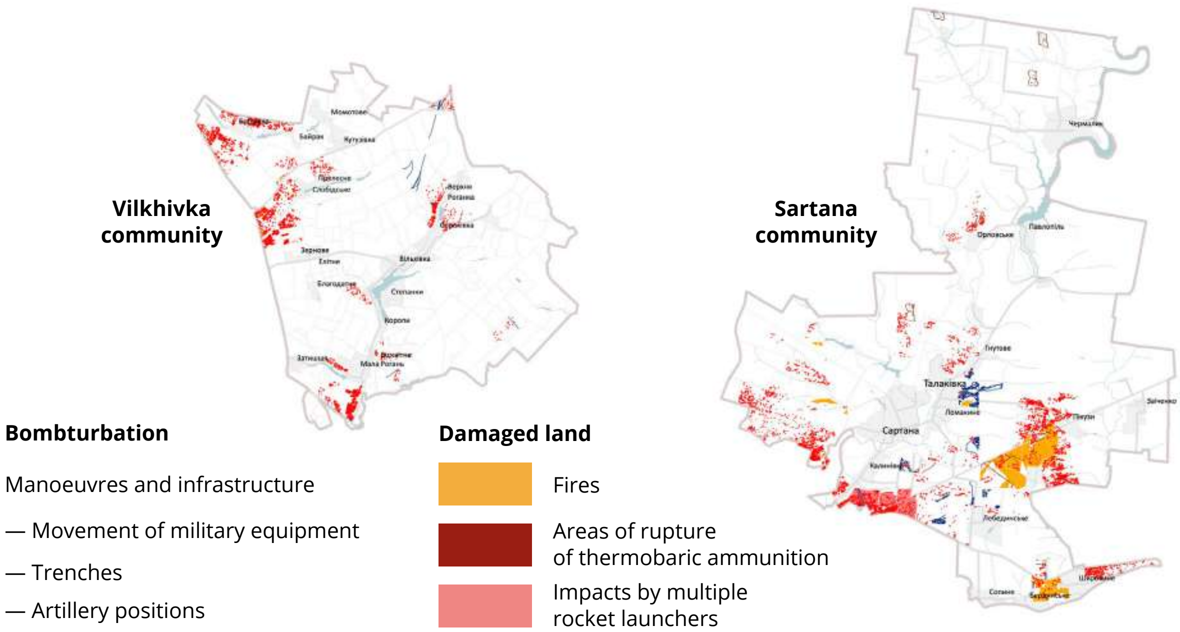


Figure 4. *Identification of impact factors*

Damages by types of impacts can then be characterised (mechanical, physical, and chemical) and primary and secondary consequences for land, with reference to specific plots, can be forecast, specifically:

- **chemical impact —** contamination of soil with chemical elements from explosions (locations of bombing, a 5 meters zone from the epicentres of the explosion);
- **mechanical impact —** littering of the territory with shrapnel after explosions due to shelling (up to 120 meters of shrapnel flying), movement of military equipment;
- **physical impact —** thermal contamination due to fires (lithogenesis, soil burning), soil compaction due to the movement of military equipment.

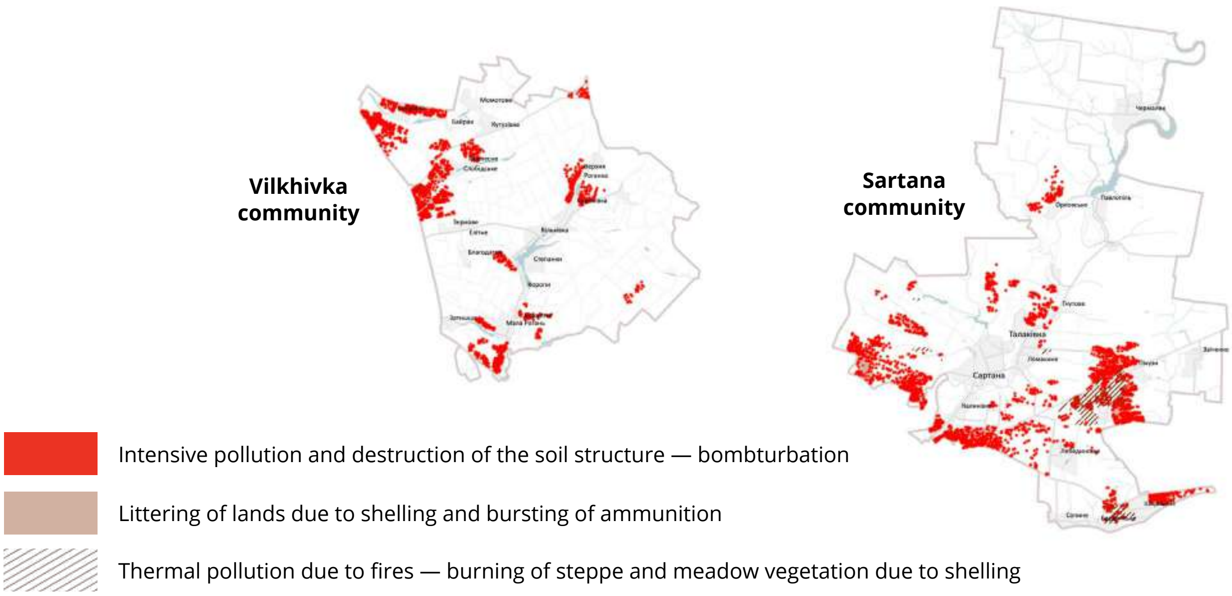


Figure 5. *Analysis of types of impact and consequences for lands*

The level of damage is key to the preliminary determination of the category of site suitability for use and decision-making on the expediency of restoration measures. As such, the level of damage due to a certain type of soil impact in a section of land must be assessed based on the proportion of the area of the site that has been damaged/contaminated. For example, when assessing the littering of areas with fragments, the larger the area of littering, the greater the level of damage, the more effort and money should be spent on cleaning (Fig. 6).

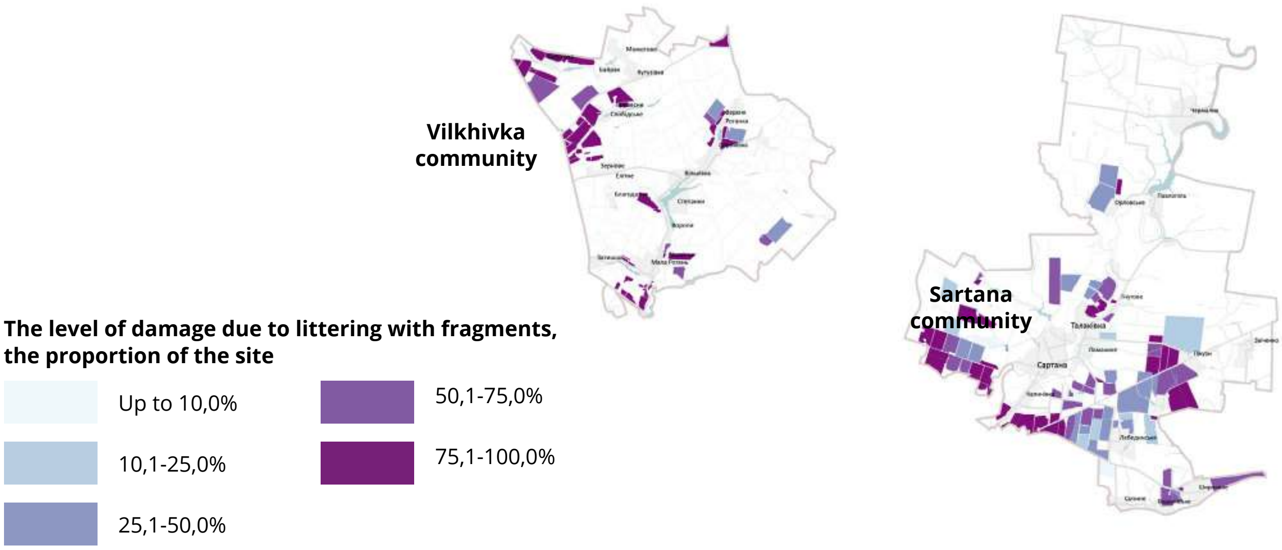


Figure 6. *Evaluation of the level of soil pollution*

The degree of chemical contamination can be pre-determined based on the intensity of shelling, which is deciphered from the space image by the number of craters formed as a result of the explosions: the greater the intensity of the explosions (the number and density of craters, continuous shelling without pauses), the greater the degree of chemical contamination of the soil should be expected (Fig. 7).

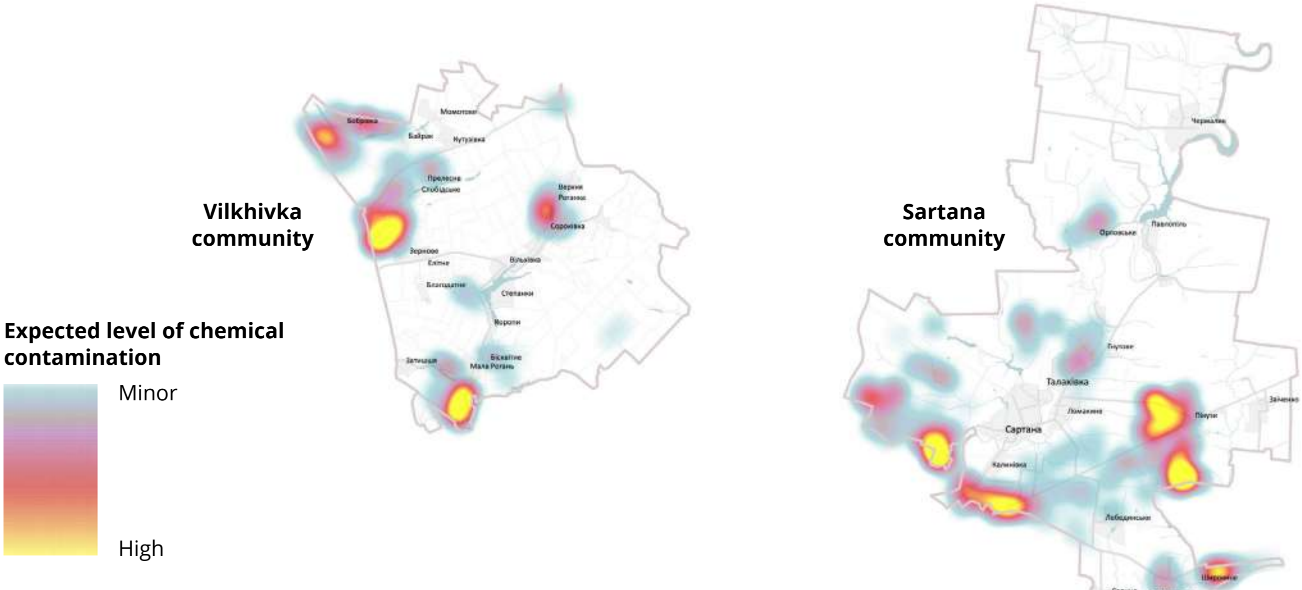


Figure 7. *Evaluation of the chemical level of soil pollution*

Results of laboratory analyses of soil in communities

The soil cover of the Vilkhivka community is represented mainly by black soil (chernozems) with ordinary low-humus light loams. It is characterised by a fairly high level of absorbed cations and humus and acidity varies from neutral to slightly alkaline — 6.4-7.4. It also contains a significant amount of silty particles (from 17% to 28%). The physico-chemical properties of the soil determines the biogenic accumulation of Zn, Cu, and Mn and the reduction of removal of Co and Ni.

During direct artillery fire, 122mm.G D-30 and 152mm.PG D-20 projectiles weighing from 6.5 to 43.56 kg were used in these territories, resulting in particles being emitted that contain high levels of lead and copper, originating from artillery shells.

The gross content of heavy metals, which are considered as indicators of war-made load, at the points of sample selection are lead (42 mg/kg), chromium (98 mg/kg), and nickel (76 mg/kg). Their content exceeds the background level and the level of maximum permissible concentration (MPC):

- cadmium (8.5 mg/kg) in 5.6 times;
- copper (168 mg/kg) in 6.4 and 5 times;
- zinc (143 mg/kg) by 2.6 times.

The content of manganese (720 mg/kg) exceeds the background value by 25 times, but is within the maximum limit.

Heavy metals in the soil have a low migration capacity and are practically not removed from the soil. While the content of heavy metals in the soil of the Vilkhivka community depends on the available sources of war-made pollution, a high degree of conformity of the nature of the distribution of heavy metals with the general regularities of these processes in black soil has been proven. The main direction of further research should thus be to identify sources of pollution and improve methods of reducing their concentration to acceptable standards.

The soil cover of the Sartana Territorial Community is represented by ordinary low-humus black soil. The total depth of the humus profile is 75-85 cm. Redistribution of colloids along the profile is not observed. The structure of the humus horizon is lumpy, whereas in the arable it is prismatic, with clear signs of compaction. The reaction of the soil solution is close to alkaline and in its natural state it is neutral. In addition:

- The cadmium content varies from 7 to 11.5 mg/kg and exceeds the MPC by 7.6 times;
- Increased copper content (50 mg/kg) was recorded in all soil samples. It exceeded background values and MPC values by 1.8 and 1.5 times, respectively;
- The zinc content is 215 mg/kg, which is 4.3 and 3.9 times the maximum limit;
- The content of lead (63 mg/kg) is 4.7 and 1.9 times higher than the MPC;
- The content of chromium (53 mg/kg) exceeds the background by 1.2, but is within the maximum limit;
- The content of nickel (50 mg/kg) exceeds the background level and the MPC level by 3.3 and 2.5 times, respectively.

The presence of contamination of the soil cover by many chemical elements has been established in the territories, with the main pollutants being lead and copper according to indicators of the gross content of metals in the soil. Furthermore, concentrations of gross forms of heavy metals exceed background values and MPC by 1.5-7.6 times.

Comprehensive assessment of the level of damage: multivariate analysis

The assessment of the level of damage to the site (Fig. 8), which takes into account the complexity of impacts and consequences in their correlation, makes it possible to predict the cumulative effects. A comprehensive multi-factorial assessment allows for a well-informed decision regarding recovery policies (conservation, abandonment, and proactive recovery actions).

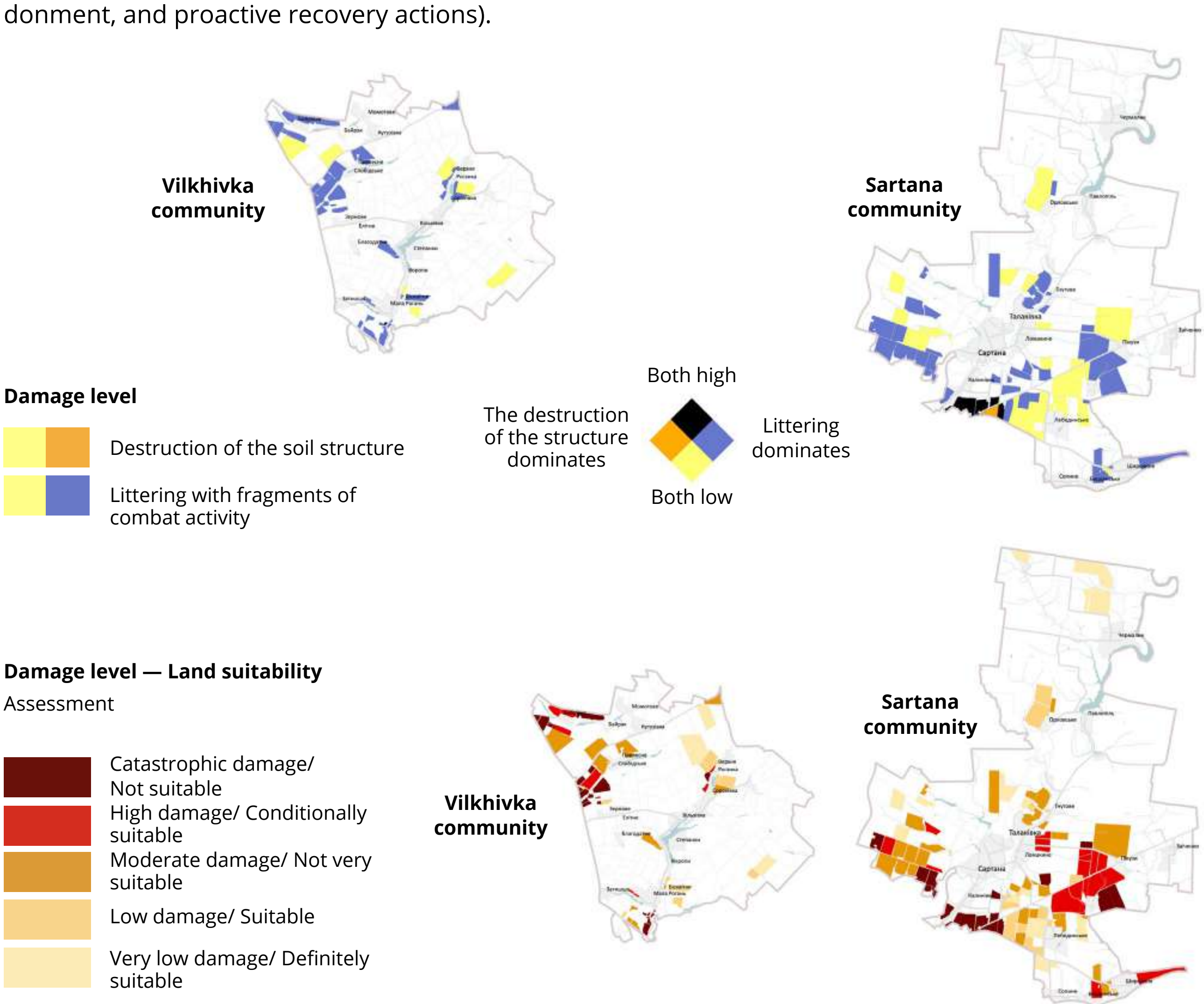


Figure 8. *Defining land recovery technologies: Vilkhivka and Sartana communities*

Depending on the adopted political decision regarding restoration actions, specific land restoration technologies are selected with the determination of the approximate cost of the works.

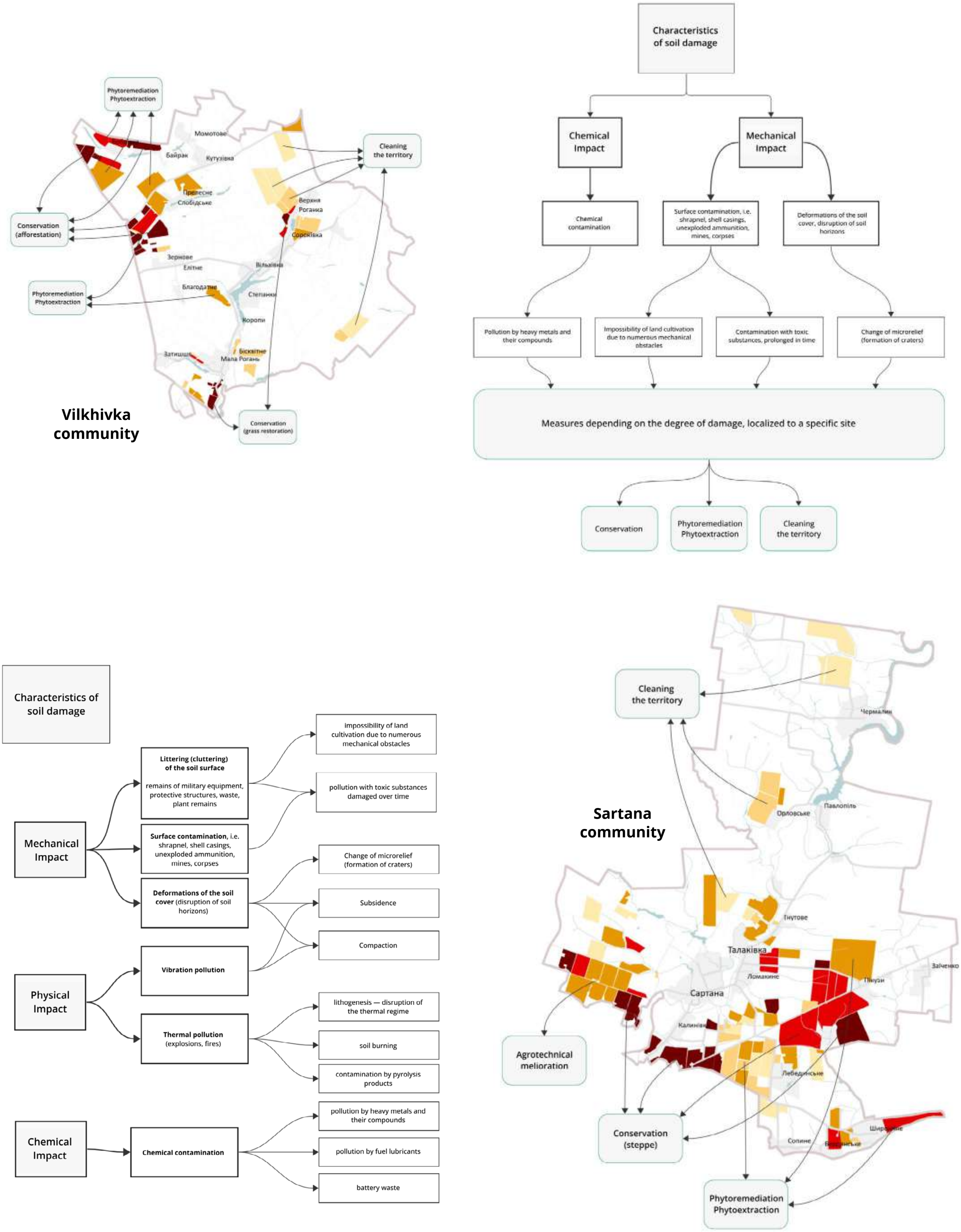


Figure 9. *Defining recovery technologies in communities*

The study recommends various land restoration practices for the sampled communities, specifically:

Conservation: Partial or complete removal of a land site from economic activity for a certain period of time. For the Sartana community, during conservation, it is recommended to carry out measures to return areas to the steppe. You can learn more about conservation practices in the next section.

Phytoremediation: Treatment of a polluted area with concentrator plants to eliminate pollutants by splitting the pollutant with plant roots into a less toxic element or absorbing the pollutant, accumulating it in the stems and leaves of the plant.

Phytoextraction: Planting of high-biomass plants that absorb and accumulate heavy metals (for example, As, Cd, Zn), excess cations (for example, Na), or nutrients (for example, PO4, NO3, NH4) in the shoots. They are then harvested and disposed of safely.

Cleaning the territory: Mechanical cleaning of the surface, maintenance of sanitary conditions.

Agrotechnical melioration: Weakening of surface runoff and transferring it to internal soil one.

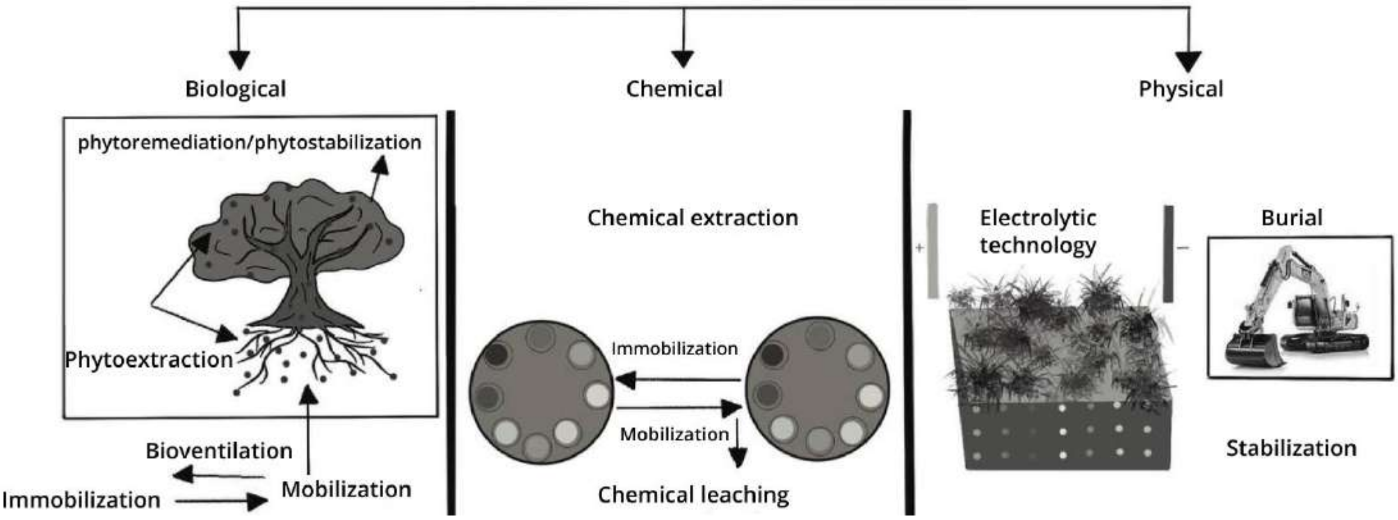
Land Restoration Practices

Although soil has a natural ability to regenerate, the independent reproduction of fertility takes place over thousands of years. To accelerate the recovery of the fertile soil layer and stop its degradation, two approaches are usually used: re-cultivation or conservation practices.

Land re-cultivation is the process of transforming contaminated land into usable land by normalising soil conditions and reducing chemical exposure to plants. This approach largely depends on the nature and degree of contamination, the intended purpose or use of the site to be restored, as well as the availability of effective and cost-effective technologies. Physico-chemical soil characteristics and climatic conditions are also important issues when choosing re-cultivation methods[43].

The choice of cleaning technology in order to optimally compensate for the impact of pollutants on the soil requires a comprehensive consideration of a combination of various factors. The main factor is the potential capabilities of technology to reduce the content of pollutants. Aspects such as costs for the implementation of the process, availability and readiness to use technology, impact on the environment, duration of the process, public opinion, and assessment of scale and cost also come in to play when making this choice.

Currently, methods of treatment of contaminated soil (Scheme 4) include physical, chemical, and biological remediation (cleaning).



Scheme 4. *Methods of treatment of contaminated soil*

[43]M.D. Fernбndez Rodrнguez, M.C. Garcнa Gуmez, N. Alonso Blazquez, J.V. Tarazona, Soil Pollution Remediation, Editor(s): Philip Wexler, Encyclopedia of Toxicology (Third Edition), Academic Press, 2014, Pages 344–355, ISBN 9780123864550

№	Technology	Estimated cost
1	Agriculture	Laboratory studies from USD 20,000 (1 m^3), pilot studies from USD 100,000; Treatment of 1 m^3 of soil up to USD 100
2	Stabilization	The cost of technology with reagents (per 1 m3) is from USD 50 to USD 120 for surface pollution, from USD 200 for deep pollution. The cost of the equipment is set separately. It is from USD 200,000, depending on the characteristics of the territory, the cost of electricity
3	Phytoremediation	The cost of 1 hectare with a capacity of 0.5 m of soil ranges from USD 150 to USD 250,000.
4	Composting	The cost of the technology depends on the amount of treated soil, the availability of additives, the type of pollutants and is USD 200 per 1 m^3 when processing 20,000 m^3 of soil
5	Chemical leaching (washing)	The cost of the technology ranges from USD 30 to USD 300 per 1 m^3 of soil, taking into account the type and concentration of substances included in the solution
6	Thermal desorption	The cost of treatment ranges from USD 10 to USD 70 per 1 m^3 of soil. Pilot studies cost from USD 10,000. The concentration of pollutants, landscape and geochemical conditions determine the upper limit of the cost
7	Chemical extraction	The cost of technology is estimated from USD 150 to USD 500 per 1 m^3 of soil
8	Chemical oxidation/redox	The cost of the entire process is estimated to be between USD 200 and USD 500 per ton of treated soil, excluding the cost of analytical studies
9	Burial	The cost of 1 ton is from USD 1,000,000

Table 1. *Estimated cost of using soil restoration technologies*

Land conservation is the practice of partially or fully restricting the use of a land site for economic purposes for a specified period of time[44]. Conservation is resorted to in the case when the use of land is neither ecologically nor economically expedient, as well as when land sites contain man-made pollution, making it impossible to obtain ecologically clean products and dangerous to the health of people present.

Conservation of such land involves grass restoration, afforestation, or renaturalisation to restore the fertile properties of the soil. In land management science, a distinction is made between **conservation-rehabilitation** — after a certain period pause, the land is returned to cultivation — and **conservation-transformation,** which means that degraded land is irreversibly removed from arable land[45].

[44] Порядок консервації земель https://zakon.rada.gov.ua/laws/show/z0810-13#n14

[45] Попов, А.С. (2022). Територіальний землеустрій. Миколаївський національний аграрний університет.

In addition to the natural characteristics of the soil and climatic conditions, the cumulative assessment of the level of damaged land is also important for the selection of restoration methods. A comprehensive assessment of all types of pollution will make it possible to outline the list of necessary measures for restoration and to mark the categories of suitability for the use of the land plot.

Damage level (% of the site area)	Land suitability categories	Characteristics of contaminated soil	Usage	Necessary measures
Very low damage (Up to 10% of the site area)	Definitely suitable	The content of chemical substances in the soil is within the background values.	Conducting agricultural activities. Cultivation of any crops.	Not required.
Low damage (10-25% of the site area)	Suitable	The content of chemical substances in the soil exceeds the background level value, but not higher than the MPC.	Use for any crops subject to quality control of agricultural products.	Implementation of agrotechnical measures to reduce the entry of metals into products (liming, application of organic and mineral fertilizers).
Moderate damage (25-50% of the site area)	Not very suitable	The content of chemicals in the soil exceeds the MPC at the limiting translocation rate.	Use for industrial crops without receiving food and feed from them; Use for hayfields and pastures with standardized grazing.	Phytoremediation, selection of agricultural crops that do not accumulate pollutants. Carrying out agrotechnical measures.
High damage (50-75% of the site area)	Conditionally suitable	The content of chemicals in the soil exceeds the MPC for most of the studied pollutants.	Use for cultural pastures; Cultivation of essential oil crops.	Anti-erosion, hydrotechnical, physical and chemical recultivation. Exclude cultivation of crops for food purposes.
Catastrophic damage (75-100% of the site area)	Not suitable	The content of chemical substances in the soil exceeds the MPC for all indicators.	Exclusion from agricultural use. Conservation.	Natural recovery

Analysis of the experience of land restoration policy in countries affected by military actions

Restoration of post-war territories is a priority component for their safe development. Under Protocol V of the Convention on Specific Types of Conventional Weapons[46], there is a legal obligation to clear, remove, or destroy explosive remnants of war. However, there is a gap regarding the normatively established requirements for land restoration in that there is no clear legal obligation to eliminate environmental pollution as a result of military activities, and efforts remain unsystematic and on a case-by-case basis. The following is an analysis of the main national policies of countries whose land resources have been affected by military operations.

United States of America (US):

In the US, land contaminated by substances of war-made origin belong to the Ministry of Defence. As such, the ministry is responsible for actions to restore this land and cannot provide these areas for rent until studies confirm the possibility of their intended use. At the same time, territories of former war-made impact, the use of which is the responsibility of local authorities, can independently initiate issues regarding their restoration.

There are 1,400 military facilities with a total area of 10 million acres[47] under the jurisdiction of the US Department of Defence. Recognising the importance of military sites in conserving biodiversity, the US has begun rehabilitating former military sites to serve as nature reserves[48]. As of 2014, measures have been developed for 15 of these areas to promote and preserve the biodiversity of these regions.

Under the drafted legislation, the responsible authority must develop a land use plan and approve the type of property, specific use of the land, and any "clearance" requirements, which must be met by the US government before the land can be put into use. To sell or lease land for a specific type of use, the Department of Defence is required to perform various site risk assessments to determine appropriate remediation measures[49] depending on the type and level of contamination.

[46] 1980 CONVENTION ON CERTAIN CONVENTIONAL WEAPONS (CCW) https://www.icrc.org/en/document/1980-convention-certain-conventional-weapons

[47] DSB. (2003). Report of the Defense Science Board Task Force on Unexploded Ordnance. Office of the Under Secretary of Defense for Acquisition and Technology. Defense Science Board. Washington, DC.

[48] Coates, P. 2014. From hazard to habitat (or hazardous habitat): the lively and lethal afterlife of Rocky Flats, Colorado. Prog. Phys. Geogr. 38(3): 286 300

[49] United States Environmental Protection Agency: Handbook on the management of munitions response actions: interim final, EPA 505-B-01-001. Washington, DC: Office of Solid Waste and Emergency Response; 2005.

United Kingdom (UK):

Pollution by substances of war-made origin in the UK is a consequence of numerous air strikes and the use of various weapons systems since World War II. This has contributed to a policy of holding landowners, not the military, responsible for the contamination of areas. Besides, local authorities often work together with landowners and share responsibility for the restoration of these lands.

The system of management of post-war territories of UK thus puts more responsibility on civilian land owners. Given this regulatory strategy, the country does not provide specific guidance for the management of these areas and has no formal quantitative standards to enable an ecological-geochemical assessment of this land.

Although the Ministry of Defence does not have detailed guidance on the management of areas contaminated by munitions, it does have a regulated approach to quantifying the risks posed by land contamination[50]. The ministry uses a land quality assessment that includes site studies based on preliminary strategic assessment and prioritisation, field and camera studies, detailed site studies, option evaluation, and local government response. Despite the shared responsibility for the restoration of post-war territories between landowners and the ministry, there is still no methodology that would effectively determine restoration measures[51].

Germany:

Substances of war-made origin are concentrated in many territories of the country. Germany's policy on these lands stipulates that all former military test sites must be investigated and potentially restored before they can be used for civilian purposes.

Abandoned military sites have been handed over to the German government since 1991, making the German government responsible for most of the contaminated land. In most cases, these areas were not cleared of unexploded ordnance and therefore the state of mine contamination for many of the decommissioned ranges has not been investigated. If the German government sells the land for restoration to the owners, they become responsible for the restoration measures[52].

Military sites are considered potentially contaminated until studies have proven that the area does not pose a danger to the environment and/or people. In this case, the study area is subject to the environmental laws and standards of the German land in which it is located. Existing laws at the national level regulate the stages of restoration of a contaminated site[53].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The step-by-step procedure of ecological and geochemical assessment of post-war territories has not been officially formalised in any country except Germany. A hazard-based (retrospective) approach identifies a toxic substance and predicts its behaviour to eliminate hazards. Within the framework of this work, an additional assessment of preventive measures is carried out in the form of systematised characteristics of pollutants.

[50] United Kingdom Ministry of Defense: Duty holders guide - guidance on the assessment and management of land contamination (IN 0708). London: Defense Estates; 2008

[51] Linkov et al. Munitions and explosives of concern: international governance and applications for the United States. Environmental Sciences Europe 2014, 26:30 http://www.enveurope.com/content/26/1/30

[52] Jcntsch, A., Friedrich, S., Steinlein, T., Bcyschlag, W., & Nezadal, W. (2009). Assessing conservation action for substitution of missing dynamics on former military training areas in Central Europe. Resiuuruiion Ecology, 2/(1), 107-116.

[53] German Federal Environment Agency: 'Germany,' Investigation, Assessment, and Clean-up of Contaminated Military Sites. 2007

During the period of research, several models of risk assessment were developed, which were used for many years to assess the territories under war-made impact. The output of the models is a summary value, which is then used to prioritise the development of the area according to the risk to the population and the environment. Despite the quantitative nature of these assessments, the priority of rehabilitating contaminated areas also depends on other factors, including regional planning, privatisation, government requests, and political decisions.

France:

World War I significantly changed the soil and plant cover in France, where the main part of the hostilities on the Western Front took place. Soils were often contaminated with heavy metals such as copper (Cu) and lead (Pb) and unexploded ordnance[54].

The West-Flanders Restoration Service is one of the first organisations that dealt with the restoration of agricultural land in damaged areas. This organisation advised local farmers and helped restore arable land. Domestic and foreign non-commercial organisations were partially engaged in the restoration of post-war territories, the most famous example of which is the Committee of Destroyed France (Comite Americain pour les Regions Devastees), which contributed not only to the social reconstruction of the village in Jena, but also distributed agricultural remnants, sowing seeds and livestock[55].

In the decade after the end of the war, it was possible to restore most of the former front-line zone – forests were replanted and agricultural lands were returned to cultivation – with the exception of the "red zone," which stretched from Lille in northern France to the south west of Nancy. The French government declared the area uninhabitable due to chemical contamination and the presence of unexploded ordnance[56]. In these areas, the cost of melioration exceeded the economic value of the land, so afforestation was preferred.

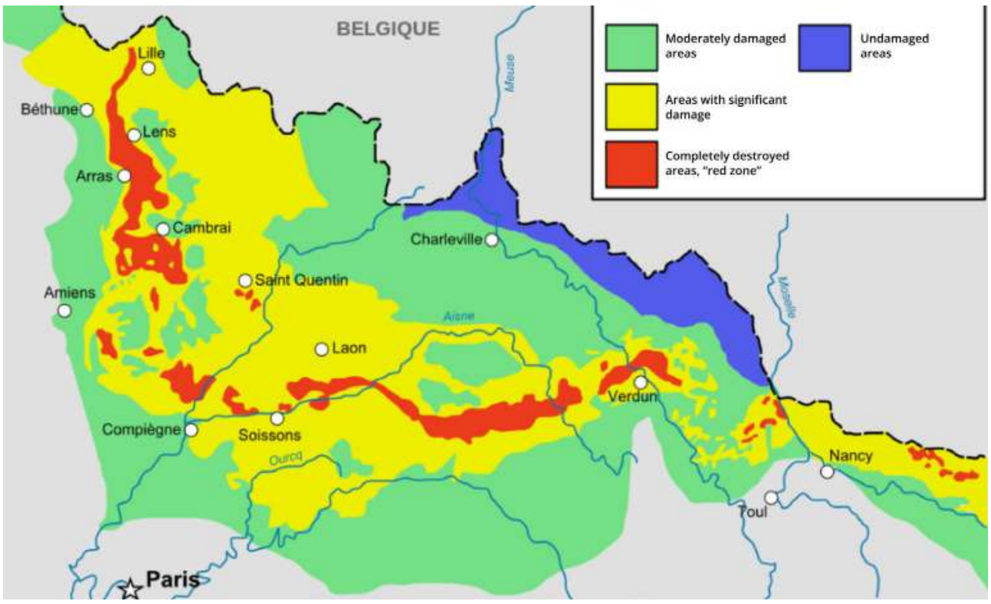

Figure 10. *Zoning of the post-war territories of France*

Note. Completely destroyed areas in red, areas of significant damage are in yellow, moderately damaged areas are in green, undamaged areas are in blue

The purpose of zoning post-war territories was to assess the possibilities of their restoration to normal economic activity. Economic considerations were also added to the criteria, that is, where the value of individual lands was too low for "clearing" considering the cost of de-mining work.

[54] Forest Service, USDA, "Status of the interior Columbia Basin: summary of scientific findings," General Technical Report (GTR) (1996): 55

[55] J. Winter, 'Introduction', in J. Winter (ed.), The legacy of the Great War: ninety years on (2009), pp. 1–17.

[56] Stuart Thornton, "Red Zone," National Geographic, May 1, 2014, http://www.nationalgeographic.org/news/redzon

Until 1919, the French Ministry of Liberated Territories divided the affected territories into three zones, depending on the level of destruction:

- "green zones" with minimal damage;
- "yellow zones" with severe but limited damage;
- "red zones," which are usually closest to the former front lines and are completely destroyed.

The green and yellow zones were returned to civilian use relatively early, while the red zones mostly had a high percentage of landscape disturbances and were cleaned only superficially, but were mainly conserved. France's Securite Civile, which is responsible for land restoration, estimates that at current rates, it could take up to 700 years to completely clear all remnants of World War I shells and grenades from French land[57].

Countries of the former Yugoslavia:

A number of armed conflicts took place in the territory of the former Republic of Yugoslavia (South Eastern Europe) between 1991 and 2001, causing significant damage to the environment, which led to the contamination of surface and underground water, soil, and air in the Balkans with more than 100 toxic substances. However, one of the most significant problems of the post-war reconstruction of these countries was institutional failure, in particular with regard to solving environmental problems[58].

Three key factors were identified:

1. The main threat was that environmental management systems would be so broken that it would be impossible to properly overcome the post-war environmental problems, while institutional failure may have exacerbated environmental "aftershocks" following the conflict.

2. At the end of the conflict, most countries had very inadequate means and resources for monitoring (Albania, Macedonia, and Romania). As such, they could not adequately measure the environmental consequences of the war, and therefore could not adequately prepare plans to deal with them.

3. The curtailment of the activities of non-governmental organisations (NGOs) in Yugoslavia due to the lack of resources, as well as political realities, stopped their cross-border activities, thereby preventing proper public involvement in environmental decision-making and planning. For example, in Kosovo, international organisations worked on the same problems in parallel and at the same time worked in different areas without the involvement of the local community[59]. Moreover, NGOs could not help overcome environmental problems where official authorities could not get involved.

At the international level, the main aid programmes of the European Union in the Republic of Serbia (including Kosovo), the Republic of Montenegro, and North Macedonia were managed by the European Agency for Reconstruction as the main EU body for the reconstruction of war damages in these countries (the mandate ended in 2008)[60]. One of the areas of programme implementation is the environment, and environmental issues were also resolved within the sectors of rural development, water bodies, and infrastructure.

[57] https://bigthink.com/strange-maps/zones-rouges/

[58] Assessment of the environmental Impact of Military Activities During the Yugoslav (Preliminary Findings, June 1999) Prepared by: The Regional Environmental Center for Central and Eastern Europe // https://reliefweb.int/report/albania/assessment-environmental-impact-military-activities-during-yugoslavia-conflict

[59] Earnest, J. & Dickie, C. (2012). Post-conflict reconstruction—a case study in Kosovo: the complexity of planning and implementing infrastructure projects. PMI Research and Education Conference.

[60] European Agency for Reconstruction // https://web.archive.org/web/20061120191411/http://www.ear.europa.eu/agency/agency.htm

Recommendations for authorities at the national and regional levels regarding ecologically sustainable and socially just restoration of disrupted and contaminated lands

National level

№	Recommendations
	Strategic Level
1	Create a National Coordinating Committee to overcome the consequences of military activity, as well as to develop measures to restore the soil cover of post-war landscapes
2	Develop a national strategy for soil recovery of post-war landscapes by 2032
3	Develop an action plan for the implementation of the strategy until 2032
4	Account for the National Strategy for soil recovery of post-war landscapes in the: • New General Scheme of Planning of the Territory of Ukraine • National Recovery Programme of Ukraine, in particular in the "Reconstruction of a clean and protected environment" projects • State's strategic documents (Sustainable Development Strategy of Ukraine by 2030; State Regional Development Strategy for 2021-2027 and a measures plan for its implementation; National Economic Strategy by 2030)
	Recommended actions for the implementation of the national strategy for soil recovery
5	Establish a Centre for Environmental Management of Post-War Territories to set standards for pollutant content (for example, maximum allowable pollutant levels) and determine appropriate levels/standards for soil treatment
6	Develop: • a system of measures for cleaning and de-mining the soil cover of post-war landscapes • zoning of the territories of post-war landscapes, taking into account the levels of their pollution and the necessary recovery measures for normal economic activity • the method of determining the amount of damage caused to the soil as a result of military actions • regulatory document regulating compensatory soil improvement
7	Carry out soil certification of post-war landscapes
8	Develop the following programs: • ecological and geochemical studies of soil in post-war landscapes within the framework of preparation of state normative documents • procedures for ecological and geochemical assessment of post-war territories and territories contaminated with substances of war-made origin • set of indicators of military-technogenic pollution that can be used to monitor soil changes

9	Implement pilot projects in de-occupied territories to assess the effectiveness of rehabilitation measures in specific post-war land
10	Ensure constant ecological and geochemical monitoring of soil according to the developed and approved network of sampling points
11	Conduct a comprehensive ecological and geochemical assessment of the soil of post-war landscapes in cooperation with international organisations for the purpose of comprehensive research and determination of priorities for restoration
12	Cooperate with local and international organisations to exchange results, conclusions, methods of improving analysis, and best practices on environmental issues of post-war reconstruction
	Cooperation with local authorities
13	Consider the possibility of direct cooperation of the Government of Ukraine with local authorities by providing expertise and re-cultivation or conservation technologies to overcome the consequences of war-made impacts
14	Support local authorities, communities, and international organisations in financing projects aimed at combatting pollution and waste disposal as well as improving the ecological infrastructure of the territories
	Compensation
15	Develop: • a regulatory and legal framework for providing a mechanism for the return (with compensation to landowners) of contaminated lands to state ownership for their restoration • an economic mechanism for regulating land relations regarding compensation to owners or tenants of land plots as a result of restrictions on their use and preliminary and full compensation to owners of the value of seized land plots • a regulatory and legal framework for providing investment to landowners and land restoration measures
16	Establish guarantees for the rights of land owners if the land is seized or temporarily conserved
17	Ensure the parity of interests of landowners, land users, and the state during the implementation of orders regarding the treatment of contaminated lands that are left in the ownership of private individuals, with the mandatory implementation of measures for their restoration
	Financing
18	Provide funding for a full independent ecological and geochemical assessment of soil, which should be initiated by the Government of Ukraine
	Informing the public
19	Implement a process of informing the public about the risks of using contaminated land (for example, creating a geoportal)

Regional level

№	Recommendations
1	Account for the National Strategy for soil recovery of post-war landscapes in: • the programmes of comprehensive restoration of the territories of regions and territorial communities (and parts thereof) • regional territory planning schemes at the local level
2	Consider the need for soil restoration at the local level when developing Comprehensive Community Development Plans or Master Plans
3	Ensure consideration of the problems of restoration of damaged soils during the strategic environmental assessment of state planning documents
4	Develop a regional soil policy within agricultural sectors with the possibility of control by local authorities of licenses for the cultivation of agricultural crops
5	Establish control over compliance with the requirements of legislation during work on the restoration of contaminated soils
6	Involve potential stakeholders in the decision-making process regarding restoration goals and evaluation of re-cultivation/conservation efforts
7	Establish a public-private partnership to expand land restoration practices (for example, between the Ministry of Agrarian Policy and Food of Ukraine and farmer groups)