G18 ГЕОДЕЗІЯ ТА ЗЕМЛЕУСТРІЙ. ЗЕМЕЛЬНІ ВІДНОСИНИ ТА АКТУАЛЬНІ ПРОБЛЕМИ ЗЕМЕЛЬНОЇ РЕФОРМИ

ISSN 2306-1677 (Print) ISSN 2518-7325 (On-line)
Received: 15.09.2026; Accepted: 15.10.2026; Published: 30.12.2026;
UDC 504.5:355.4:623.746-519 http://dx.doi.org/10.31548/zemleustriy2026.04.06

ENVIRONMENTAL CONSEQUENCES OF MILITARY ACTIONS: AN ANALYSIS OF ENVIRONMENTAL POLLUTION CAUSED BY UNEXPLODED ORDNANCE, INFRASTRUCTURE DAMAGE AND DEBRIS FROM UNMANNED AERIAL VEHICLES

O. KEMPA,
Doctor of Technical Sciences, Senior Lecturer
Email: olgierd.kempa@upwr.edu.pl
ORCID: 0000-0002-5153-2010
Wroclaw University of Environmental and Life Sciences
ZH. VYRVA,
Master of Engineering Sciences, Assistant
Email: joanna.wyrwa@upwr.edu.pl
ORCID: 0000-0002-2540-8999
Wroclaw University of Environmental and Life Sciences
A. KOSHEL,
Doctor of Economic Sciences, Professor
Email: koshel_a@nubip.edu.ua
ORCID: 0000-0001-9032-1622
National University of Life and Environmental Sciences of Ukraine
M. KEMPA,
Student
Email: 131984@student.upwr.edu.pl
ORCID: 0009-0000-6084-9338
Wroclaw University of Environmental and Life Sciences
A. ROZAK,
Master of Engineering Sciences, Director
Email: angeo@onet.pl
ORCID: 0009-0007-3238-5514
AnGeo Enterprise

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution-ShareAlike 4.0 International License (https://creativecommons.org/licenses/by-nc-sa/4.0/)

Abstract. *Armed conflicts leave a lasting mark on the environment. They alter the landscape and leave behind materials whose presence does not cease with the end of hostilities. The aim of this study is to categorise such residues. Four main criteria have been adopted: source, area of distribution, mechanism of impact and material properties. The study draws on research findings from former battlefields, military sites and areas of current conflict. It examines munitions remnants, metals, energy materials, chemicals, radionuclides, fuel, technical waste and permanent changes to the terrain. Examples from France, Belgium, Vietnam, Kosovo, the Persian Gulf region and Ukraine show that environmental pressure can arise in various ways. It may occur at the site of weapon deployment, at the site of equipment destruction, during the subsequent handling of remnants, or as a result of changes in land use. In this broader context, unmanned systems are proposed as a new subject of study regarding technical remnants. Their construction involves a variety of materials. It covers metals, polymers, composites, electronics and energy sources. Fibre-optic cables are also used in some FPV systems. When a platform is lost, they can leave a linear trail on the ground. The scale of this phenomenon and its environmental consequences are as yet unknown. The available data do not allow these residues to be compared with well-studied munitions residues. Therefore, this article is primarily of a systematic and identificatory nature. It sets out directions for further research: spatial inventory, material identification, assessment of degradation and migration, as well as studies into the potential impact on soil, water, vegetation and fauna.*

Keywords: *armed conflict, environmental pressure, munitions, soil contamination, unmanned systems, geoinformation.*

Relevance

War causes social, material and environmental damage. This paper does not consider the consequences for human health and life. We are interested in the natural environment and the material legacy of military operations that remains in the landscape after they have ended.

Hostilities cease, but what they have left behind in the landscape does not simply disappear. Studies of former battlefields show that craters, metals from munitions debris, energetic compounds and the breakdown products of chemical shells can persist in the soil for decades (Certini et al., 2013; Broomandi et al., 2020). A hundred years after the First World War, differences in soil development and elevated levels of copper and lead are still evident in the forest soils of France (Williams & Rintoul-Hynes, 2022). For such areas, it is well known what contaminants are present and how these behave under different conditions.

The situation is now becoming more complex. The Russia–Ukraine war has become the first major conflict in which unmanned systems play a leading role and are being used in very large numbers. A significant proportion of these platforms are single-use: after completing their mission, they crash or are left behind on the ground. A drone contains metals, polymers, composites, electronics and batteries (Negi et al., 2025); in other words, its composition differs markedly from that of a shell or a mine. Some FPV systems are controlled via a fibre-optic cable that is unwound during flight (Tytarenko et al., 2025). Once the platform is lost, the cable may remain on the ground as a linear object for

which there are no analogues amongst conventional military debris.

This issue has received almost no scientific attention. Ukrainian studies have already documented soil degradation, craters and changes in land use (Solokha et al., 2023, 2024; Bonchkovskyi et al., 2025; Domashenko et al., 2025), but these focus primarily on the consequences of munitions use. The remnants of unmanned systems—their quantity, spatial distribution, rate of degradation and environmental impact—are not specifically addressed in these studies. We have neither field measurements nor established terminology, nor any idea as to whether this is a significant phenomenon or a minor one. It is impossible to inventory and study such debris until it is clear to which category they belong and by what criteria they should be described.

Therefore, the need for systematisation arises before the need for measurements. This article does not claim that the debris from unmanned systems constitutes a proven class of pollution. It places them within a broader classification of military debris, clearly distinguishes known facts from hypotheses, and identifies what exactly should be investigated further. For Ukraine, where reconstruction and environmental assessment of territories are only just beginning, such a classification will help to lay the right foundations for spatial inventory and field research at an early stage.

Analysis of recent research and publications

As regards unmanned systems, their structure and multi-material nature have been well documented (Balestrieri et al., 2021; Negi et al., 2025; Hashim, 2025). The use of fibre-optic communication channels in some FPV systems has also been documented (Tytarenko et al., 2025). However, there is still a lack of sufficient data on the number of UAV remnants left behind after military operations, their location, rates of degradation and impact on specific ecosystems. This is primarily due to the period during which unmanned systems began to play a leading role on the battlefield. This period is, in essence, limited to the ongoing conflict between Russia and Ukraine, which significantly affects the ability to obtain direct field data.

Consequently, this paper does not specify the proportion of UAV debris in the total mass of military debris. Nor does it determine a universal half-life for a drone or cable. In the absence of empirical data, no specific toxicological effects are attributed to particular materials. Such limitations are necessary to avoid conflating technical information, mechanistic hypotheses and environmental outcomes.

This article represents the first stage of a research programme. Its aim is to define the problem and systematise existing knowledge. Subsequent studies should move from identification to quantitative measurements and the assessment of mechanisms. This phased approach reduces the risk of drawing conclusions that are not supported by the available data.

Aim and objectives of the study

The aim of this article is to systematise knowledge regarding the environmental consequences of wars, based on previous research. The second aim is to demonstrate the role played by unmanned systems within this context. Particular attention is paid to the classification of debris and its spatial

characteristics. Unmanned systems are considered as a proposed new subject of research. We do not claim that they already constitute a proven, distinct category of pollution.

Materials and methods

This paper is a review. It draws on scientific publications concerning the environmental consequences of conflicts, soil contamination, unexploded ordnance, energy materials, chemical weapons and radionuclides. In addition, publications on unmanned systems, their classification, structure and construction materials have been utilised.

Examples were selected primarily so that they could be compared. For field studies, the location and time of data collection were taken into account, provided that the publication clearly stated this information. Measurement results were separated from mechanistic interpretations. A further restriction was applied with regard to unmanned systems: information on the structure of the devices is not considered as evidence of the presence of a specific contaminant in the environment.

The analysis was based on four elements. The first is the source of the residue. The second is the location where it is found. The third covers the mechanism of impact. The fourth concerns persistence and the potential for transport. This approach makes it possible to compare conventional military remnants with materials left behind by modern technical systems.

Results

The environmental impact of a conflict has two main dimensions. The first is changes to the environment. These include soil degradation, loss of vegetation, changes to the water cycle and alterations to the landscape. The second dimension consists of material remnants. These include, in particular, munitions, metals, explosive materials, fuel, parts of vehicles and infrastructure, as well as waste generated during military operations. Both groups often occur together. They may also interact with one another (Certini et al., 2013; Broomandi et al., 2020).

The environmental significance of these residues depends on their composition, form and location. Environmental conditions are also important. The same material may behave differently in different soils and under different water conditions. The mere presence of an object does not, in itself, answer the question of its impact. It is necessary to distinguish between the source and the residue, as well as the pathway of movement from the environmental component that may be affected.

Advances in military technology have also altered the nature of the materials left behind following its use. The industrialisation of warfare has increased the significance of artillery munitions, fuel and chemical substances. In the 20th century, radionuclides and chemical agents, deployed on a large scale, were added to this list. Modern military systems, in turn, contain an increasing amount of electronics, composites, polymers and power systems. This does not in itself imply the emergence of a new class of contamination. However, it does provide grounds for identifying new categories of residues and assessing whether they require different detection methods.

Classification of environmental military debris

There is no single, universally accepted classification of the environmen-

tal consequences of war. Certini et al. (2013) categorise impacts on soil into physical, chemical and biological effects. Broomandi et al. (2020) focus on pollution associated with military activities and on groups of substances present in the environment. In this paper, both approaches are used as a starting point for our own organisation of the material.

Two independent criteria have been adopted. The first addresses the question of where and in what form the traces of conflict remain. The second describes the manner in which pressure is exerted on the environment. The criteria may overlap. The same object may belong to several classes if it combines different mechanisms of impact.

Along the first axis, four groups have been identified: remnants of weapons, remnants of the immediate frontline zone, remnants of military equipment, and remnants from areas behind the front lines.

Remnants of weapons of war include, in particular, shell fragments, structural elements, explosive materials, unexploded ordnance and soil displaced during detonation. A blast crater is both a geomorphological feature and a record of the weapon's action. It alters the local topography. It can also affect infiltration, water runoff and erosion.

The immediate frontline zone comprises trenches, positions, fortifications, tunnels, shelters and field tracks. This group also includes domestic waste and other debris left behind in areas where troops were stationed for extended periods. The removal of vegetation, soil compaction and the displacement of material are physical consequences observed here. Changes to the flora and fauna should be regarded as a consequence of the impact, rather than as physical remains.

Remains of military equipment include vehicle wreckage, components of the powertrain, metal parts, plastics, rubber and glass. They also include fuel, oils, operating fluids, batteries and electronics. Modern unmanned systems represent a new and distinctive category within this group. Their significance for further research is determined primarily by the number of components and the variety of materials.

Non-combat zones encompass areas subject to rear-area bombing, destroyed industrial and energy infrastructure, warehouses, transport networks and public utilities. Land-use changes associated with population displacement and concentration may also be taken into account here. Environmental pressure may therefore arise far from the immediate theatre of hostilities.

The second axis addresses the mechanisms by which pressure is exerted on the environment. Conventional actions lead to detonation, the formation of craters, the fragmentation of munitions, soil displacement and the creation of debris. Chemical effects encompass both the deliberate use of substances and their subsequent release during storage, incineration or disposal. Radioactive materials require separate consideration due to their physical properties. Indirect impacts include changes in land use, hydrology and ecosystem functioning.

This distinction helps to avoid confusing the source with the effect. A crashed vehicle is a technical residue. Fuel that has leaked from its tank is a source of potential chemical pressure. A change in the concentration of a substance in the soil is already an observable effect. The same approach should be followed when analysing the residues of unmanned systems.

Ammunition remnants and physical changes to the terrain

Ammunition remnants are among the best-studied types of military environmental debris. Broomandi et al. (2020) highlight the presence of metals and energetic compounds in areas associated with military activity. Certini et al. (2013) also draw attention to the formation of craters, trenches, soil compaction and soil displacement.

The First World War provided a wealth of material for comparison. Primarily due to the scale of artillery use. Bausinger et al. (2007) investigated the consequences of the post-war destruction of chemical munitions in the Verdun area of France. After the war, this area was used for the incineration of shells containing arsenic compounds. High concentrations of arsenic and metals were detected in the topsoil. This demonstrates that the handling of residues can itself become a secondary source of contamination.

Thouin et al. (2016) investigated the mobility of arsenic and heavy metals in the soil of the Place-à-Gaz area in the Spincourt Forest, approximately 20 km north-east of Verdun. The area was associated with the post-war destruction of shells containing arsenic compounds. The results confirmed the importance of soil properties for the movement of contaminants. This is also relevant for other debris. The mere fact that material lies on the soil surface does not in itself indicate how far it can travel.

Williams and Rintoul-Hynes (2022) analysed soils in the forests of the Pas-de-Calais department in France, in an area that had been subjected to shelling during the First World War. The study was carried out approximately one hundred years after the end of hostilities. Differences in soil development linked to the presence of shell craters were identified. However, no significant differences in heavy metal concentrations were found between the craters and flat areas. At the same time, higher concentrations of Cu and Pb were observed compared with the regional background values. The results clearly demonstrate the extent to which local conditions can alter the distribution of war remnants.

Van Meirvenne et al. (2008) investigated the possibility of localising metal remnants in former frontline areas of Belgium. This work highlights the importance of combining two aspects: the object remaining in the soil and the method used to locate it spatially. Historical military remnants can therefore constitute both an environmental and a geospatial issue.

Chemical sources of environmental pressure

Chemical contamination associated with war has at least two sources. The first is the direct use of chemical substances. The second is the subsequent release of substances contained in munitions, depots, industrial facilities and infrastructure. In the latter case, the problem may only arise after hostilities have ceased.

Bausinger et al. (2007) demonstrated this mechanism using the example of a chemical munitions incineration site in the Verdun area. The results indicate that the method of dealing with residues can be just as significant as the very fact that they are left behind. This is of direct importance for the assessment of post-war measures and remediation.

Vietnam presented a different kind of pressure. Operation Ranch Hand took place between 1961 and 1971. Herbicides were sprayed from the air to limit vegetation cover. Stellman et al. (2003) analysed revised data on the scale and spatial distribution of the spraying. The

analysis covered Vietnam, as well as data on Laos and Cambodia. This case demonstrates that military operations can deliberately alter vegetation over a very large area.

The destruction of infrastructure can create new, secondary sources of pollution. Fires at industrial plants, warehouses and energy facilities can release materials stored within these sites. Certini et al. (2013) and Broomandi et al. (2020) classify such processes as physical and chemical consequences of military activity. In modern conflicts, this mechanism may be of significant importance due to the quantity of substances accumulated within the infrastructure.

Radioactive materials as an example of a specific residue

Radioactive materials form a distinct group of residues. Their specific characteristics are determined, in particular, by the possibility of identifying the source on the basis of isotopic properties and by the long-term persistence of some radionuclides. The examples of Hiroshima and Nagasaki show that, when interpreting the current presence of radionuclides, a distinction must be made between global fallout and material directly associated with the weapon used.

Yamamoto et al. (1985) analysed Pu, ^{241}Am and ^{137}Cs in soils from Hiroshima and Nagasaki. The samples were taken from areas associated with the bombings of 6 and 9 August 1945. In the Nishiyama area of Nagasaki, the isotopic ratios indicated a significant proportion of plutonium originating from the bomb. In Hiroshima, the interpretation was more complex. This example clearly demonstrates that the mere detection of a radionuclide is not sufficient. It is also important to establish its origin.

During the Gulf War, a different mechanism was at work. Bem and Bou-Rabee (2004) analysed the environmental consequences of the use of depleted uranium. Their review covered data from Kuwait and southern Iraq, in particular measurements from 1992–1994. The authors considered the possibility of corrosion of metallic uranium and the migration of the products of this process. At the same time, they did not find widespread exceedances of drinking water quality criteria in the studied part of Kuwait. This is a good example of the difference between potential mobility and confirmed exceedances of regulatory limits.

Danesi et al. (2003) investigated depleted uranium particles in selected samples from Kosovo approximately 1.5 years after the end of hostilities. They identified fine particles of depleted uranium (DU) and analysed the potential for their transport. This case highlights the importance of particle size for the spatial distribution of residues.

The non-military dimension of influence

The environmental impact of war is not necessarily linked to the location of direct hostilities. Land-use changes, population displacement, the establishment of camps, restrictions on access to certain areas, or changes in the way infrastructure operates can all have an impact. Such pressures may develop beyond the area where weapons are being used.

Hagenlocher et al. (2012) analysed a camp for internally displaced persons in North Darfur, Sudan. They used multi-temporal, very high-resolution satellite imagery. The analysis covered the years 2002, 2004 and 2008. As the camp's area and population increased, a reduction in the number of trees and shrubs and the degradation of part of the surrounding area were observed.

The study shows that remote sensing makes it possible to track environmental changes even beyond the immediate combat zone.

Rose (2005) analysed the impact of military activities on local and regional geological conditions. He drew particular attention to explosions, roads, airfields and fortifications. A common feature of these activities is a change in surface geometry and soil properties. For contemporary research, this implies the need to view the territory as a carrier of two types of information: material remains and persistent spatial changes.

Modern unmanned systems as a proposed new area of research

Unmanned systems should not be equated solely with aerial drones. Balestrieri et al. (2021) describe systems operating in the air, on land, and both on and beneath the water's surface. Hereinafter, the abbreviations UAV/UAS are used for aerial platforms, UGV for ground-based platforms, USV for surface vessels and UUV for underwater vehicles.

In this article, the primary focus of analysis is on UAVs. Today, it is easier to link their remnants to the observable actions of modern conflicts. However, this does not mean that the proposed category applies only to aerial platforms. UGVs, USVs and UUVs can be analysed using a similar material and spatial framework.

Technical literature describes UAVs using a variety of parameters. Chamola et al. (2021) take into account, in particular, mass, propulsion type, operating altitude and purpose. Balestrieri et al. (2021) focus on the sensors and measurements used in unmanned systems. From an environmental perspective, however, a comprehensive operational classification is not the most important factor. It is far more important what the device is made of and what form it may take after it is lost.

Negi et al. (2025) draw attention to the multi-material composition of drones and analyse it in the context of the life cycle. The structures contain metals, polymers and fibre-reinforced composites. There are also electronic components and energy storage systems. However, the results of the life-cycle analysis cannot be directly applied to the behaviour of military debris. The publication describes the composition of the structure. It does not show the actual release of substances from the debris into the environment.

Hashim (2025) describes the avionics architecture, which encompasses communications, power supply, sensing, navigation, trajectory planning and control. The debris left behind by a UAV is therefore not limited to the airframe. Following the loss of the entire system, electronic components, power sources, cables, optical components and structural elements may remain in the environment.

Four groups of UAV debris have been proposed for environmental research. The first covers structural elements. The second covers functional components. The third covers power sources. The fourth covers auxiliary and operational materials. This is a working classification. Its purpose is to organise the research, rather than to create a formal taxonomy.

The structural group comprises metals, polymers and composites. The functional group comprises electronics, cables, sensors, optical systems and communication components. The energy group consists primarily of batteries. The auxiliary group includes adhesives, resins, coatings and insulation. Negi et

al. (2025) provide a basis for material identification. However, their data do not allow the proportion of individual components in actual military UAV debris to be determined.

On the modern battlefield, the number of unmanned systems in use is very high. A significant proportion of these are regarded as single-use systems and are abandoned or destroyed after completing their mission. The spatial form of the debris is also important. Debris can be recorded as a point or surface object. Fragments may form a cluster of dispersed objects. In some FPV systems, linear debris may also occur.

Tytarenko et al. (2025) describe the use of fibre-optic cables in FPV systems in conflict situations. The cable creates a physical connection between the platform and the operator. During operation, it is unwound from a reel. After the platform is lost, part of it may remain along the flight path. In this case, a thin, long and spatially continuous element is formed. It differs from a single piece of debris in both its shape and the method by which it can be inventoried.

At present, there are not enough field studies to determine the typical length of cable remaining after the loss of a single platform. Nor is it possible to specify a universal degradation time for the entire cable. The cable has a layered structure. The core may be made of glass or plastic, whilst the protective sheaths are made of polymeric materials. The rate of ageing depends on the specific design and exposure conditions.

In the case of cables, two issues need to be distinguished. The first concerns the fate of the material. The second concerns its physical presence in the environment. The possibility of organisms becoming entangled in cables remains, at this stage, a research hypothesis. Without field data, it should not be presented as a confirmed environmental impact.

The most important argument for singling out UAV debris as a subject of research is its as yet unproven toxicity. This relates to the changing nature of technical debris. A single system contains many materials, which distinguishes it from traditional weapons. Once part of the system is lost, these materials may become dispersed. Some platforms may also leave a linear trail. This gives rise to a problem whose scale cannot currently be determined on the basis of the literature.

It is proposed that UAV debris be considered as a research category within the broader group of military equipment debris. The word ‘new’ here refers to the subject of the research. It does not imply that the existence of a new mechanism of contamination is accepted. The hypothesis needs to be tested. Quantitative measurements, material identification, monitoring of degradation and environmental studies are required.

Spatial and geospatial significance

Each of the categories described has its own spatial geometry. A crater is a surface feature. A piece of munition is usually in the form of a point or a small surface feature. Vehicle debris can be localised as a point. Destroyed infrastructure, on the other hand, must be represented as an area. Therefore, the classification of debris must also take into account the geometry of the observed object.

In the case of a UAV, the location where debris is detected does not necessarily correspond to the launch site. It may be associated with the location where the platform was lost, where it broke up, or with the cable route. In FPV systems, linear geometry takes on particular significance. Recording

a cable as a polyline makes it possible to determine its length, orientation and spatial density.

Research conducted in Ukraine shows that data on surface changes can be combined with environmental analysis. Solokha et al. (2023) used field and remote sensing data to assess changes in soil and vegetation. Bonchkovskyi et al. (2025) applied high-resolution spatial data to identify craters and analyse soil disturbances in north-eastern Ukraine. Domashenko et al. (2025) highlight the usefulness of geodetic methods, GNSS, UAVs, LiDAR and GIS for monitoring land-use changes in Ukraine during the period of Russian aggression and reconstruction.

In the forthcoming inventory of UAV debris, it is advisable to record at least the coordinates, the date of observation, the data source, the type of object, its condition and an assessment of the accuracy of its location. This data can be combined with soil maps, hydrography, land cover and land use information. The analysis will then not be limited to the question of where the debris is located. It will also be possible to examine the environment in which it is found.

A geoinformation approach is particularly useful where direct access to the area is restricted. Remote sensing can help to detect changes in the surface and locate some of the objects. Determining the material composition, however, requires field or laboratory investigations. If an image does not provide grounds for unambiguous identification of the material, it should not replace measurements.

Discussion

The literature confirms the presence of environmental residues from munitions, military equipment and war-related industrial activities. Physical transformations of the territory and the persistence of some of these changes have also been confirmed (Certini et al., 2013; Broomandi et al., 2020; Rodríguez-Seijo et al., 2024). However, these findings cannot be directly applied to UAV debris.

In the case of unmanned systems, their structure and multi-material nature have been well documented (Balestrieri et al., 2021; Negi et al., 2025; Hashim, 2025). The use of fibre-optic communication channels in some FPV systems has also been documented (Tytarenko et al., 2025). At the same time, there is still a lack of sufficient data on the number of UAV debris following military operations, its spatial distribution, rate of degradation and impact on specific ecosystems. This is primarily due to the relatively recent period in which unmanned systems began to play a leading role on the battlefield. It is effectively limited to the Russia–Ukraine conflict, which significantly affects the ability to obtain direct field data.

Therefore, this study does not specify the proportion of UAV debris in the total mass of military debris. Nor is a universal degradation time for drones or cables determined. Specific materials are not attributed particular toxicological effects without empirical data. Such limitations are necessary to avoid conflating technical information, mechanistic hypotheses and environmental outcomes.

This article represents the first stage of a research programme. Its aim is to define the problem and organise existing knowledge. Subsequent work should move from identification to quantitative measurement and the assessment of mechanisms. This division into stages reduces the risk of drawing conclusions that are not supported by the available data.

Conclusions and prospects for further research

1. Military operations leave behind both permanent physical changes to the environment and materials that may become a source of subsequent pressure.

2. For research purposes, two complementary classification frameworks are proposed. The first describes the location and form of the residue. The second describes the mechanism by which pressure arises.

3. The best-studied remnants are munitions, metals, energy materials, chemical compounds and some radionuclides. Their behaviour depends on both the properties of the material and environmental conditions.

4. Unmanned systems should currently be classified as military equipment remnants. However, their multi-material composition and the potential for their components to be dispersed provide grounds for considering them as a separate subject of research.

5. Fibre-optic cables are used in some FPV systems. Following the loss of the platform, they may form linear debris. However, there is a lack of data that would allow for a quantitative assessment of their presence and environmental significance.

6. At present, there are no grounds for considering UAV debris to be a proven, distinct class of pollution. The category presented in this paper is intended as a research proposal.

7. Further research should combine geoinformation-based inventorying, material analysis, studies of degradation and migration, and an assessment of the impact on specific environmental components.

Declaration on the use of artificial intelligence

Whilst preparing this manuscript, the authors used a generative artificial intelligence tool (Claude, Anthropic) for linguistic and stylistic editing, structuring the text and translating the abstract into English. After using this tool, the authors personally checked, edited and reviewed the content and bear full responsibility for the scientific accuracy, data, interpretations and conclusions. The AI tool was not used to generate scientific results, sources, citations or numerical data.

References

1. Balestrieri, E., Daponte, P., De Vito, L., & Lamonaca, F. (2021). Sensors and measurements for unmanned systems: An overview. *Sensors*, 21(4), Article 1518. DOI: https://doi.org/10.3390/s21041518
2. Bausinger, T., Bonnaire, E., & Preuss, J. (2007). Exposure assessment of a burning ground for chemical ammunition on the Great War battlefields of Verdun. Science of the Total Environment, 382(2–3), 259–271. DOI: https://doi.org/10.1016/j.scitotenv.2007.04.029
3. Bem, H., & Bou-Rabee, F. (2004). Environmental and health consequences of depleted uranium use in the 1991 Gulf War. *Environment International*, 30(1), 123–134. DOI: https://doi.org/10.1016/S0160-4120(03)00151-X
4. Bonchkovskyi, O., Ostapenko, P., Bonchkovskyi, A., & Shvaiko, V. (2025). War-induced soil disturbances in north-eastern Ukraine (Kharkiv region): Physical disturbances, soil contamination and land use change. Science of the Total Environment, 964, Article 178594. DOI: https://doi.org/10.1016/j.scitotenv.2025.178594
5. Broomandi, P., Guney, M., Kim, J. R., & Karaca, F. (2020). Soil contamination in areas

impacted by military activities: *A critical review. Sustainabili*ty, 12(21), Article 9002. DOI: https://doi.org/10.3390/su12219002

6. Certini, G., Scalenghe, R., & Woods, W. I. (2013). The impact of warfare on the soil environment. Earth-Science Reviews, 127, 1–15. DOI: https://doi.org/10.1016/j.earscirev.2013.08.009
7. Chamola, V., Kotesh, P., Agarwal, A., Naren, Gupta, N., & Guizani, M. (2021). A comprehensive review of unmanned aerial vehicle attacks and neutralization techniques. Ad Hoc Networks, 111, Article 102324. DOI: https://doi.org/10.1016/j.adhoc.2020.102324
8. Danesi, P. R., Markowicz, A., Chinea-Cano, E., Burkart, W., Salbu, B., Donohue, D., Ruedenauer, F., Hedberg, M., Vogt, S., Zahradnik, P., & Ciurapinski, A. (2003). Depleted uranium particles in selected Kosovo samples. Journal of Environmental Radioactivity, 64(2–3), 143–154. DOI: https://doi.org/10.1016/S0265-931X(02)00045-0
9. Domashenko, H., Monar, D. S., & Prokopenko, N. (2025). Geodetic support for monitoring changes in the land use structure of Ukraine during the period of Russian armed aggression and post-conflict recovery. *Land Management, Cadastre and Land Monitoring*, (2), 20–32. DOI: https://doi.org/10.31548/zemleustriy2025.02.02
10. Hagenlocher, M., Lang, S., & Tiede, D. (2012). Integrated assessment of the environmental impact of an IDP camp in Sudan based on very high resolution multi-temporal satellite imagery. Remote Sensing of Environment, 126, 27–38. DOI: https://doi.org/10.1016/j.rse.2012.08.010
11. Hashim, H. A. (2025). Advances in UAV avionics systems architecture, classification and integration: A comprehensive review and future perspectives. Results in Engineering, 25, Article 103786. DOI: https://doi.org/10.1016/j.rineng.2024.103786
12. Negi, H., Vedrtnam, A., & Kalauni, K. (2025). Materials and energy-centric life cycle assessment for drones: *A review. Journal of Composites Science,* 9(4), Article 169. DOI: https://doi.org/10.3390/jcs9040169
13. Pichtel, J. (2012). Distribution and fate of military explosives and propellants in soil: A review. Applied and Environmental Soil Science, 2012, Article 617236. DOI: https://doi.org/10.1155/2012/617236
14. Rodríguez-Seijo, A., Fernández-Calviño, D., Arias-Estévez, M., et al. (2024). Effects of military training, warfare and civilian ammunition debris on the soil organisms: An ecotoxicological review. Biology and Fertility of Soils, 60, 813–844. DOI: https://doi.org/10.1007/s00374-024-01835-8
15. Rose, E. P. F. (2005). Impact of military activities on local and regional geologic conditions. *Reviews in Engineering Geology*, 16, 51–66. DOI: https://doi.org/10.1130/2005.4016(05)
16. Solokha, M., Pereira, P., Symochko, L., Vynokurova, N., Demyanyuk, O., Sementsova, K., Inacio, M., & Barcelo, D. (2023). Russian-Ukrainian war impacts on the environment: Evidence from the field on soil properties and remote sensing. Science of the Total Environment, 902, Article 166122. DOI: https://doi.org/10.1016/j.scitotenv.2023.166122
17. Solokha, M., Demyanyuk, O., Symochko, L., Mazur, S., Vynokurova, N., Sementsova, K., & Mariychuk, R. (2024). Soil degradation and contamination due to armed conflict in Ukraine. *Land,* 13(10), Article 1614. DOI: https://doi.org/10.3390/land13101614
18. Stellman, J. M., Stellman, S. D., Christian, R., Weber, T., & Tomasallo, C. (2003). The extent and patterns of usage of Agent Orange and other herbicides in Vietnam. Nature, 422(6933), 681–687. DOI: https://doi.org/10.1038/nature01537
19. Suleimenov, I., Kadyrzhan, A., Vitulyova, Y., Shaltykova, D., et al. (2025). The use of fiber optics for securing information during

command transmission to UAV groups. International Journal of Information Technology. DOI: https://doi.org/10.1007/s41870-025-02719-2
20. Tytarenko, O., Abramov, S., Ktitorov, M., & Synytsina, Y. (2025). Countering FPV drones: Insights from Ukraine's combat experience. *Advances in Military Technology,* 20(2), 421–434. DOI: https://doi.org/10.3849/aimt.01998
21. Van Meirvenne, M., Meers, E., Verstraete, S., Smolders, E., & Tack, F. M. G. (2008). Could shelling in the First World War have increased copper concentrations in the Belgian soil? Science of the Total Environment, 391(2–3), 170–179. DOI: https://doi.org/10.1016/j.scitotenv.2007.10.007
22. Williams, O. H., & Rintoul-Hynes, N. L. J. (2022). Legacy of war: Pedogenesis divergence and heavy metal contamination on the WWI front line a century after battle. European *Journal of Soil Science*. DOI: https://doi.org/10.1111/ejss.13297
23. Yamamoto, M., Komura, K., Sakanoue, M., Hoshi, M., Sawada, S., & Okajima, S. (1985). Pu isotopes, 241Am and 137Cs in soils from the atomic bombed areas in Nagasaki and Hiroshima. *Journal of Radiation Research*, 26(2), 211–223. DOI: https://doi.org/10.1269/jrr.26.211

Кемпа О., Вирва Ж., Кошель А., Кемпа М., Розак А.

ЕКОЛОГІЧНІ НАСЛІДКИ ВОЄННИХ ДІЙ: АНАЛІЗ ЗАБРУДНЕННЯ ДОВКІЛЛЯ ЗАЛИШКАМИ БОЄПРИПАСІВ, РУЙНУВАННЯМ ІНФРАСТРУКТУРИ ТА УЛАМКАМИ БЕЗПІЛОТНИХ СИСТЕМ

ЗЕМЛЕУСТРІЙ, КАДАСТР І МОНІТОРИНГ ЗЕМЕЛЬ 4'26: 85-97
http://dx.doi.org/10.31548/zemleustriy2025.04.06

Анотація. *Збройні конфлікти залишають у довкіллі тривалий слід. Вони змінюють територію і залишають матеріали, присутність яких не припиняється разом із бойовими діями. Метою цієї роботи є впорядкування таких залишків. Прийнято чотири основні критерії: джерело, місце поширення, механізм впливу та властивості матеріалу. Використано результати досліджень колишніх полів битв, військових територій і районів сучасних конфліктів. Розглянуто залишки боєприпасів, метали, енергетичні матеріали, хімічні речовини, радіонукліди, паливо, технічні відходи та стійкі зміни поверхні території. Приклади з Франції, Бельгії, В'єтнаму, Косова, регіону Перської затоки та України показують, що екологічний тиск може виникати порізному. Він може з'являтися в місці застосування зброї, у місці знищення техніки, під час подальшого поводження із залишками або внаслідок змін у використанні простору. У цьому ширшому контексті безпілотні системи запропоновано розглядати як новий об'єкт дослідження технічних залишків. Їхня конструкція є багатоматеріальною. Вона охоплює метали, полімери, композити, електроніку та джерела енергії. У частині FPV-систем також застосовуються оптоволоконні кабелі. Після втрати платформи вони можуть залишати на місцевості лінійний слід. Поки що невідомі масштаб цього явища та його екологічні наслідки. Наявні дані не дають змоги порівняти ці залишки з добре дослідженими залишками боєприпасів. Тому стаття має насамперед систематизувальний та ідентифікаційний характер. Вона визначає напрями подальших досліджень: просторову інвентаризацію, матеріальну ідентифікацію, оцінку деградації та міграції, а також дослідження можливого впливу на ґрунт, воду, рослинність і фауну.*

Ключові слова: *збройний конфлікт, екологічний тиск, воєнні залишки, забруднення ґрунтів, безпілотні системи, геоінформація.*