ISSN 2669-2023 (print) / ISSN 2538-8959 (on-line) / **https://doi.org/10.47459/cndcgs.2026.85**

Assessing the Environmental Impacts of Artillery Activity and Fostering Regional Cooperation for Post-Conflict Soil Ecosystem Recovery

Martin BLAHA[1], Jan IVAN[1], Vladimír ADAMEC[2], Natálie GOTTVALDOVÁ[1], Martin HERCÍK[1]*

[1]Department of Fire Support, Faculty of Military Leadership, University of Defence, Kounicova 65, 602 00, Brno, Czech Republic
[2]Institute of Forensic Engineering, University of Technology, Purkyňova 118, 612 00, Brno, Czech Republic

*Correspondence:*martin.hercik@unob.cz*

Abstract

This paper develops an integrated analytical framework for assessing the environmental impacts of artillery activity on soil ecosystems. The approach combines military-technical parameters with environmental, spatial, and economic data using GIS and geostatistical methods. A key contribution is the Environmental Burden Index (EBI), which evaluates environmental load across five domains: chemical contamination, physical degradation, spatial distribution of impacts, ecological sensitivity and recovery complexity. The results demonstrate that environmental degradation arises from the interaction of multiple factors, particularly fire intensity, munition type, terrain morphology, and soil characteristics, rather than from isolated contamination indicators. The proposed framework enables objective comparison of affected sites, identification of remediation priorities, and supports decision-making processes in post-conflict recovery and sustainable land management.

KEY WORDS: *Artillery; Soil Contamination; Post-Conflict; Recovery; Environmental Security; Regional Development.*

Citation: Blaha, M.; Ivan, J.; Adamec, V.; Gottvaldová, N.; Hercík, M. Assessing the Environmental Impacts of Artillery Activity and Fostering Regional Cooperation for Post-Conflict Soil Ecosystem Recovery. In Proceedings of the Challenges to National Defence in Contemporary Geopolitical Situation, Brno, Czech Republic, 7-10 September 2026. ISSN 2538-8959, https://doi.org/10.47459/cndcgs.2026.85

1. Introduction

Contemporary armed conflicts confirm with unprecedented clarity that artillery activity generates, in addition to its immediate kinetic and destructive effects, a massive environmental footprint. This footprint has long-term and often irreversible impacts on the stability, security, and overall resilience of affected regions. In the context of armed forces' approaches to environmental protection, it is evident that the degradation of soil ecosystems is initiated not only by explosions and munition fragmentation but primarily by the deposition of explosive residues and other contaminants of both inorganic and organic origin [1]. Similar conclusions are supported by studies identifying long-term accumulation of heavy metals and explosive residues in military training areas [2]. This represents a major obstacle to future agricultural production, the reconstruction of destroyed infrastructure, and the subsequent resettlement of populations back into affected areas [3]. The environmental dimension of conflict thus constitutes an inseparable component of post-conflict recovery and fundamentally influences the future security and socio-economic development of the region [4].

In this context, however, the environmental dimension of artillery activity is often reduced in academic literature to isolated chemical analyses or partial ecological indicators, rather than being understood as a complex systemic interaction between the type of munitions used, the intensity of fire, the physical-chemical properties of the soil environment, terrain morphology, and the institutional capacity for recovery [5]. This reductionist approach contrasts with broader assessments emphasizing the systemic environmental burden of military systems, including their energy intensity and logistical complexity [6]. The result is a fragmented assessment that confirms the presence of contaminants but fails to clarify the causal links between the characteristics of fire and the extent of subsequent damage, as well as the real impact of such damage on regional stability [1]. The absence of methodological integration of military-technical data with environmental analysis therefore prevents effective prioritization of remediation measures and limits decision-making processes in post-conflict reconstruction [7].

The first step toward understanding the entire chain of impacts is the analysis of physical degradation. Intensive artillery fire dramatically alters terrain morphology. Craters from explosions not only disrupt soil hydrological conditions but also become critical obstacles to mobility. For these purposes, methodologies for assessing terrain trafficability after artillery strikes have been detailed [8]. Research demonstrates that crater dimensions created on various geological substrates limit the mobility of military equipment; however, in the post-conflict phase, they present an identical problem for heavy remediation, construction, and agricultural machinery. Comparable physical degradation effects have been documented in military training areas, where repeated mechanical disturbance leads to soil compaction and reduced infiltration capacity [9]. The analysis of these physical changes must therefore be the primary input for evaluating the overall degradation of an area.

Obtaining precise data from contaminated and physically disrupted areas requires the deployment of modern technologies that minimize risk to human personnel. The use of Unmanned Ground Vehicles (UGVs) offers new perspectives for artillery reconnaissance and primary soil sampling in hazardous environments [7]. This direction is consistent with broader research on robotic autonomous systems, which emphasizes their growing relevance for future operational environments and their potential to increase military capabilities in tasks where direct human presence is limited, risky, or inefficient. In addition, research on combat UGV swarms demonstrates that autonomous platforms can be coordinated through digital terrain models, relief models, weather data, and force-deployment information, which is directly relevant for planning reconnaissance routes and sampling missions in artillery-affected terrain [7; 25; 26]. This is followed by the necessity of precise mapping using Unmanned Aerial Vehicles (UAVs) equipped with LiDAR technologies. UAV-based reconnaissance should therefore be understood not only as a means of collecting visual or elevation data, but also as part of a broader decision-support architecture. Constructive simulation experiments confirm that UAV reconnaissance can significantly influence mission effectiveness and can be repeatedly tested under variable tactical conditions. At the same time, the use of UAVs in complex battlefield environments must account for electronic warfare, detection, and non-destructive counter-UAV measures, which may reduce the reliability or availability of sensor-derived environmental data [10; 11; 27; 28]. The fusion of digital surface models allows for the high-precision identification of the extent of cratering and structural changes in the landscape [10; 11]. Accurate environmental assessment is further complicated by insufficient transparency in military emission reporting, which limits the availability of reliable data [12]. The speed and accuracy of collecting these geodetic and topographic data are crucial for the subsequent modelling of contaminant spread within the soil profile and for the logistical planning of recovery operations [13]. However, such data acquisition cannot be assumed to take place under ideal technological conditions. In high-intensity or electronically contested environments, GNSS signals, meteorological support, and automated fire-control systems may be degraded, denied, or unavailable. For this reason, artillery-related environmental assessment should remain compatible with alternative coordinate-determination techniques, backup meteorological products, and contingency or emergency manual procedures for calculating firing data [29; 30; 31].

Technical and environmental data cannot be analysed in a vacuum; they must be embedded within an economic framework that determines the capacity of a state or alliance to address the situation. It is necessary to apply models for determining the rational level of defence expenditure under conditions of expected risk. Modern approaches therefore challenge fixed political percentages of GDP and instead propose resource allocation based on the valuation of national wealth, the probability of attack, and the expected rate of damage [14]. This logic can be further strengthened by utility-based decision-making approaches, which combine operational effectiveness with economic efficiency when evaluating the structure and contribution of military capabilities. Applied to post-conflict environmental recovery, such reasoning supports the prioritization of remediation measures according to both environmental burden and expected strategic utility, especially where resources are insufficient for comprehensive restoration of all affected sites [14; 16; 36]. These costs are closely linked to the high energy and resource demands of military operations, which significantly contribute to overall environmental burden [15].

Specifically, the "expected rate of damage" must integrally include the massive costs of environmental remediation of land following artillery strikes. Costs associated with decontamination of heavy metals and toxic explosive residues represent an extreme economic burden that can threaten the financial stability of a state far beyond the horizon of the conflict itself. A deteriorated security situation also has a direct impact on the financial stability of defence companies operating in an oligopolistic market, affecting the entire defence industry and its ability to generate resources for post-conflict technologies [16]. For a deeper grasp of this problem, the implementation of environmental risk assessment procedures is essential, which modern literature identifies as an inevitable foundation for sustainable military planning and economic calculation of war impacts [5].

For the newly developed analytical framework to be functional, it must be integrated into the process of command, control, and officer education. The communication environment in automated artillery fire command and control systems must now expand to include the ability to share not only tactical but also environmental and sensor data across domains [17]. Such expansion requires decision-support tools that can process heterogeneous inputs and translate them into operationally understandable options. War-gaming, utility-based assessment, AI-supported speech-to-text systems, and simulation environments for teaching and research all demonstrate that modern fire-support planning increasingly depends on rapid data processing, scenario comparison, and structured evaluation of alternative courses of action [18; 19; 36; 42; 43; 44]. Fire control officers must be trained to understand the consequences of their actions. Comparative analyses of artillery officer education therefore emphasize the challenges associated with interoperability within "Joint Fires" operations [18]. A proposed unified educational model should thus include modules for future commanders focused on evaluating collateral, long-term, and environmental damage on the battlefield. Constructive simulation tools enable the evaluation of artillery unit effectiveness in defensive scenarios, including the protection of firing positions, and provide valuable support for decision-making and training processes [19]. Modern approaches to artillery training increasingly rely on virtual and AI-supported simulation environments that enable realistic decision-making training without the need for live-fire exercises [20]. In this context, the Environmental Burden Index could be incorporated into war-game and simulation-based training as an additional assessment layer. This would allow future commanders to compare tactical effectiveness with expected environmental burden, recovery complexity, and long-term regional consequences before selecting a course of action [42; 44; 45].

This text develops a systematic analytical framework linking the military-technical parameters of artillery activity with its environmental and socio-economic consequences. It assumes that understanding soil ecosystem degradation requires the integration of data on munition types with detailed chemical and morphological analysis. Only by linking these operational and natural science data with risk-based economic models can a tool be created that enables objective site assessment, effective quantification of remediation costs, and rational prioritization of steps necessary for post-conflict recovery and the return to regional stability.

2. Methodology

The article is based on a comparative analytical synthesis of four evidence streams. The first stream consists of military-technical variables describing artillery activity, above all munition type, fuse setting, fire intensity, and spatial concentration of impacts. The second stream consists of environmental evidence, especially crater-centred soil sampling, contaminant identification, and the interpretation of contamination gradients. The third stream consists of terrain and geospatial evidence, including crater geometry, digital elevation models, and the effects of shelling on mobility and subsequent access for remediation equipment. The fourth stream consists of institutional and economic evidence, because environmental damage becomes strategically relevant only when translated into recovery time, restoration cost, and governance capability. The integration of these streams also requires methods capable of processing incomplete, directional, cyclical, or expert-based data. Circular statistics and nonparametric kernel density estimation provide useful tools for modelling directional or periodic patterns, while fuzzy expert systems can support real-time threat or burden evaluation under uncertainty. At the material level, advanced particle and speciation analysis further shows that environmental interpretation may depend not only on total contaminant concentration, but also on particle size, chemical form, and the distribution of metals within fine fractions [32; 33; 34; 35]. This logic follows recent Czech research on artillery environmental assessment, terrain mobility after shelling, defence-environment governance, and military expenditure analysis [3; 8; 21; 22]. Modelling and simulation of artillery fire enable the evaluation of fire effectiveness, ammunition consumption, and operational outcomes under complex and variable conditions that cannot be fully replicated through real-world experimentation [23]. In addition, unmanned aerial vehicles (UAVs) equipped with LiDAR can be employed for high-resolution terrain mapping and crater identification, enabling accurate spatial data acquisition in hazardous or inaccessible environments.

The methodological core of the article is the assumption that environmental burden must be reconstructed from the point of impact outward, not from generalized area averages inward. In practice, this means that the crater is treated as the primary analytical unit because it reflects the interaction between the projectile, soil horizons, blast energy, and fragment dispersion. Recent work on artillery impact zones shows that crater-centred sampling improves the identification of ammunition-specific pollution and yields a more defensible basis for chemical interpretation than non-specific surface sampling. At the same time, research on terrain mobility demonstrates that crater geometry is not merely a morphological outcome but a variable with direct implications for accessibility, counter-mobility, engineering support, and reconstruction logistics [8; 3].

Operational fire data:

→ munition and fuse characterization,
→ crater localization and terrain mapping,
→ crater-centred soil sampling,
→ laboratory analysis of contaminants and residues,
→ GIS integration of chemical, morphological, and land-use layers,
→ environmental burden scoring,
→ prioritization of remediation and recovery measures.

The proposed workflow is intentionally modular. It can be applied in active military training areas, in reference zones used for model development, or in post-conflict territories where data are incomplete and access is restricted. Its purpose is not to replace detailed local environmental surveys, but to create a common structure through which operational, environmental, and economic data can be compared and turned into an expert decision-support tool. To support the analytical logic of the workflow, a conceptual model of the relationship between fire intensity and environmental burden components is introduced in the following section, providing a structured interpretation of how individual variables interact within the Environmental Burden Index (EBI).

3. Proposed Environmental Burden Model

The analytical framework developed here organizes environmental burden into five mutually reinforcing domains: chemical contamination, physical degradation, spatial distribution of impacts, ecological sensitivity, and recovery complexity. Physical degradation captures crater formation, soil compaction, altered infiltration, erosion risk, and obstruction to movement. Ecological sensitivity addresses the vulnerability of habitats, species assemblages, water bodies, and regenerative processes. Recovery complexity measures the degree to which contamination, unexploded ordnance, damaged transport networks, and degraded terrain slow restoration. This domain should also include secondary explosive and engineering-related effects that may complicate recovery beyond the immediate crater zone. Modelling of sympathetic detonation, artillery-created minefield breaches, blast-induced structural deformation, and constructive simulation of artillery operations shows that explosive effects can generate additional constraints for access, safety, infrastructure repair, and clearance activities. Recovery complexity therefore depends not only on contamination levels, but also on the interaction between explosive hazards, structural damage, obstacle systems, and the availability of engineering resources [19; 23; 37; 38; 39]. Strategic significance is not treated as a core domain of the Environmental Burden Index but as an external prioritization layer supporting decision-making. It evaluates whether a site is important for agriculture, habitation, transport, defence infrastructure, or critical public functions. Transport and logistics deserve particular attention within this domain, because post-conflict recovery depends on the ability to move personnel, equipment, samples, construction materials, and remediation technologies through degraded terrain and damaged infrastructure. Research on terrain mobility after artillery fire, military transport shocks, cargo securing, and railway infrastructure resilience indicates that road quality, vehicle condition, crater morphology, and transport bottlenecks can substantially influence both military operations and regional recovery capacity [8; 13; 40; 41]. In this framework, environmental burden is not a single concentration value but a composite of interacting pressures that must be interpreted together [5].

Table 1.

Proposed environmental burden indicator set for artillery-affected areas

Domain	**Core indicator**	**Typical evidence source**	**Why it matters for recovery**
Chemical contamination	Concentration and gradient of ammunition-related residues and heavy metals	Crater-centred soil sampling, laboratory analysis	Determines toxic burden, decontamination method, and future land-use restrictions
Physical degradation	Crater depth, crater radius, soil structure disruption, compaction	Field survey, UAV/LiDAR mapping, terrain models	Shapes mobility, drainage, erosion risk, and engineering access
Spatial distribution	Impact density, fragment fields, clustering of damaged points	GIS, remote sensing, strike logs	Distinguishes localized hotspots from area-wide degradation
Ecological sensitivity	Habitat rarity, hydrological connectivity, protected species, regenerative capacity	Ecological survey, conservation data	Prevents technically efficient but ecologically destructive remediation
Recovery complexity	UXO burden, access routes, availability of machinery, seasonal constraints	Engineering reconnaissance, command data	Explains why equally contaminated localities may differ sharply in restoration time and cost

The practical value of this scheme is that it prevents the underestimation of damage in areas where contaminant concentrations may appear moderate, but recovery complexity is high. Conversely, it also prevents overreaction in places where concentrations are elevated, yet the site is spatially limited, ecologically resilient, and quickly accessible for remediation. The framework thereby links environmental science with operational planning rather than treating them as separate worlds.

The proposed Environmental Burden Index (EBI) formalizes the interaction of the identified domains and is defined as follows:

$$EBI = w_1C + w_2P + w_3S + w_4E + w_5R \quad (1)$$

where:
EBI – Environmental Burden Index;
C – chemical contamination;
P – physical degradation;
S – spatial distribution of impacts;
E – ecological sensitivity;
R – recovery complexity;
w_1–w_5 – weighting coefficients reflecting the relative importance of each domain.

The model assumes that environmental burden results from the interaction of multiple domains rather than a single dominant factor. Each component contributes to the overall degradation and influences the recovery potential of the affected area. The weighting coefficients may be adjusted depending on the operational context, allowing the model to reflect different priorities such as ecological protection, infrastructure recovery, or economic significance. The application of the proposed model enables the identification of high-burden zones and the comparison of artillery-affected areas based on their environmental and recovery characteristics. The results of this application are presented in the following section.

The proposed Environmental Burden Index (EBI) formalizes the interaction of multiple domains and assumes that environmental impact emerges from their combined and nonlinear effects. To illustrate the theoretical behaviour of the model, a conceptual relationship between fire intensity and individual EBI components is presented in Figure 1.

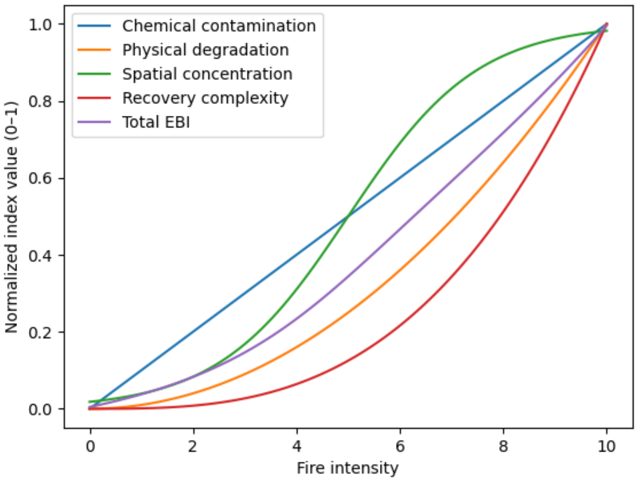

Fig. 1. Relationship between fire intensity and Environmental Burden Index (EBI) components

The relationships shown in Figure 1 correspond to the structure of the Environmental Burden Index defined in Equation (1), where individual components contribute to the overall index with different growth dynamics. Figure 1 demonstrates that individual domains contributing to environmental burden exhibit different growth dynamics as fire intensity increases. Chemical contamination follows a near-linear trend, reflecting the proportional accumulation of residues. In contrast, physical degradation and recovery complexity show nonlinear behaviour, with a significant acceleration at higher levels of fire activity. Spatial distribution of impacts reveals a threshold effect, where initially dispersed impacts transition into concentrated hotspots. The combined EBI curve reflects the interaction of these domains and highlights the nonlinear escalation of environmental burden. This supports the assumption that environmental impact cannot be adequately described by a single factor but must be understood as a system of mutually reinforcing processes. The figure is conceptual and based on simplified functional relationships designed to reflect the theoretical behaviour of individual domains defined in Equation (1). It does not represent empirical measurements but serves as a structural illustration of the model.

4. Discussion

The application of the proposed Environmental Burden Index (EBI) confirms that the environmental impact of artillery activity emerges from the interaction of multiple domains rather than from a single dominant factor. The results demonstrate that areas exposed to repeated and spatially concentrated artillery fire exhibit significantly higher EBI values due to the cumulative effects of physical degradation, contaminant accumulation, and increased recovery complexity. A key finding is that chemical contamination alone does not provide a sufficient explanation of environmental burden, as areas with only moderate contaminant levels may still reach high EBI values when physical disruption and recovery constraints are considered. This supports the argument that environmental assessment must integrate operational and spatial parameters rather than relying solely on chemical analysis [3]. At the same time, the analysis shows that physical degradation represents a critical component of environmental impact, particularly in the early stages of post-conflict recovery. High crater density, soil compaction, and altered hydrological conditions significantly limit terrain accessibility and complicate engineering operations, which corresponds with research identifying crater morphology as a decisive factor influencing operational and reconstruction capabilities [8]. This empirical interpretation is consistent with the conceptual model presented in Figure 1, which illustrates the nonlinear interaction of individual environmental burden components as fire intensity increases.

Spatial modelling within the framework further confirms that artillery activity produces highly heterogeneous patterns of environmental burden rather than uniform degradation. Affected areas are characterized by localized hotspots where contamination and physical disruption accumulate, primarily because of repeated targeting and high fire intensity that led to the concentration of heavy metals and explosive residues in confined zones. Comparable contamination patterns have been documented in military training environments, where repeated disturbance results in elevated concentrations of toxic elements [2]. Another important result is the role of recovery complexity as a differentiating factor between sites with otherwise comparable contamination levels. This behaviour corresponds to the nonlinear growth of recovery complexity illustrated in Figure 1, where logistical and technical constraints significantly amplify overall environmental burden at higher levels of disturbance. Areas affected by unexploded ordnance, damaged infrastructure, and limited access routes exhibit significantly higher EBI values due to increased technical and logistical demands for remediation, highlighting the necessity of incorporating operational constraints into environmental assessment models. The results also indicate that environmental burden is strongly influenced by the duration and intensity of artillery operations, as high operational tempo and prolonged presence of military units generate cumulative effects that exceed the impact of individual firing events. The increasing use of UAV-based systems further enhances data acquisition capabilities and operational efficiency in environmental assessment of artillery-affected areas [24]. This observation aligns with studies emphasizing the energy intensity and logistical complexity of military systems as key drivers of environmental impact [6; 9]. Overall, the findings confirm that the environmental footprint of artillery activity is a multidimensional and nonlinear process requiring integrated assessment across chemical, physical, spatial, and operational domains.

The results also highlight that effective post-conflict soil ecosystem recovery cannot be achieved solely through isolated military or environmental interventions but requires coordinated regional cooperation across multiple institutional domains. This includes the integration of armed forces, civil administration, environmental agencies, transport authorities, and scientific institutions within a shared data and decision-support framework. The proposed Environmental Burden Index (EBI) provides a common analytical language that can facilitate this cooperation by enabling standardized assessment, prioritization, and communication of environmental risks and recovery needs across actors. Such coordination is essential for ensuring interoperability of data, efficient allocation of limited resources, and alignment between environmental remediation, infrastructure restoration, and regional development strategies.

5. Conclusions

The findings of this study highlight the need to reconsider how the environmental impacts of artillery activity are conceptualized within both military and environmental analytical frameworks. Rather than being treated as a secondary consequence or a set of isolated indicators, environmental degradation emerges as an inherent and structurally embedded outcome of operational processes, shaped by the interaction of tactical decisions, technological parameters, and environmental conditions. This perspective aligns with established understanding that military activities generate complex and long-term environmental effects that cannot be reduced to single-factor analysis. The conceptual representation of the Environmental Burden Index further supports this perspective by demonstrating that environmental impact emerges from the interaction of multiple domains with distinct growth dynamics, rather than from a single dominant factor.

At the same time, the proposed framework demonstrates the importance of overcoming the fragmentation that typically characterizes the relationship between military analysis, environmental science, and economic planning. By providing a unified structure for interpreting environmental burden, it enables the integration of diverse data streams into a coherent analytical logic that can be applied across different phases of conflict and recovery. This approach reflects contemporary developments in environmental risk assessment, where integrated and multidimensional models are considered essential. Its relevance is particularly evident in post-conflict environments, where effective recovery depends not only on identifying damage, but also on aligning environmental priorities with operational feasibility and resource constraints.

The broader implications of the study indicate that the environmental consequences of artillery activity must be understood in relation to long-term system resilience rather than short-term damage alone. Environmental degradation directly affects land usability, infrastructure restoration, and the potential for population return, thereby influencing the socio-economic trajectory of affected regions. These interdependencies highlight the link between environmental degradation and broader security and economic stability.

From an applied perspective, the model establishes a conceptual and methodological basis for expanding the role of environmental data within military command and control structures. Its structured approach creates conditions for incorporating environmental indicators into planning and decision-support systems, enabling more informed and adaptive responses in complex operational environments. At the same time, its implementation requires a shift in professional military education, particularly in the context of interoperability and modern joint operations. This shift is reflected in the adoption of AI-driven training systems enabling continuous performance evaluation and individualized training.

Future research should focus on the empirical validation and calibration of the proposed Environmental Burden Index (EBI) across diverse operational and environmental conditions. This includes testing the model using real-world datasets from both military training areas and post-conflict zones, as well as conducting sensitivity analyses of the weighting coefficients to assess their influence on the overall index. Further work is also needed to compare the EBI with existing environmental assessment methodologies to evaluate its robustness, transferability, and practical applicability. In addition, future research should examine the potential of UAV-based sensing technologies for automated data acquisition and real-time monitoring of artillery-affected areas, reflecting the broader trend of increasing integration of UAV-based sensing technologies across complex operational environments. However, the effectiveness and reliability of UAV-derived data for these purposes must be systematically validated, particularly in relation to their ability to capture relevant environmental indicators and support integrated modelling approaches.

At the same time, artillery capabilities may also have selected dual-use applications in crisis management, as demonstrated by research on the potential use of specialized artillery-delivered fire-suppressant munitions in wildfire response. In a broader strategic context, the study contributes to the evolving discourse on environmental security by demonstrating that the environmental footprint of military activity should be understood as an intrinsic dimension of contemporary conflict dynamics. This does not reduce the environmental risks associated with artillery activity, but it shows that future civil-military cooperation should assess both the environmental burden of military systems and their possible contribution to emergency response, regional resilience, and protection of critical natural assets [22; 46].

Acknowledgements. This work was supported by Czech Ministry of Defence from project LANDOPS (grant number DZRO-FVL22-LANDOPS) and by the Czech Ministry of Education, Youth and Sports from project Modernization of the Czech Armed Forces Artillery training using simulation technologies (grant number SV25-FVL-K107-KOR).

References

1. N. Horáková, P. Maňas, O. Rolenec, and T. Palasiewicz, "National Defense and Environmental Protection: On the Czech Armed Forces´ Approach to the Development of Environmental Legislation in the Czech, EU and NATO Context", *Vojenské rozhledy*, vol. 31, no. 4, Dec. 2022, doi: 10.3849/2336-2995.31.2022.04.172-202.
2. K. Lach, Š. Bernatíková, L. Frišhansová, K. Klouda, and V. Mička, "STUDY OF AIR CONTAMINATION BY HEAVY METALS AT FIRING RANGES", *WIT Transactions on Ecology and the Environment*, vol. 1, Jun. 2018, doi: 10.2495/air180031.
3. J. Ivan, M. Šustr, J. Gregor, L. Potužák, and J. Varecha, "Advancing soil sampling techniques for environmental assessment of artillery impact zones", *Journal of Ecological Engineering*, vol. 26, no. 5, May 2025, doi: 10.12911/22998993/196688.
4. J. Odehnal, J. Neubauer, A. Olejníček, J. Boulaouad, and L. Brizgalová, "Empirical Analysis of Military Expenditures in NATO Nations", *Economies*, vol. 9, no. 3, Jul. 2021, doi: 10.3390/economies9030107.
5. J. Ivan, K. B. Niesner, M. Blaha, H. Doležalová Weissmannová, and V. Adamec, "Environmental risk assessment of artillery-impacted soils contaminated by heavy metals using pollution indices", *Management of Environmental Quality: An International Journal*, Feb. 2026, doi: 10.1108/meq-06-2025-0420.
6. O. Belcher, P. Bigger, B. Neimark, and C. Kennelly, "Hidden carbon costs of the "everywhere war": Logistics, geopolitical ecology, and the carbon boot-print of the <scp>US</scp> military", *Transactions of the Institute of British Geographers*, vol. 45, no. 1, Jun. 2019, doi: 10.1111/tran.12319.
7. J. Ivan, M. Sustr, O. Pekar, and L. Potuzak, "Prospects for the Use of Unmanned Ground Vehicles in Artillery Survey", *Proceedings of the 19th International Conference on Informatics in Control, Automation and Robotics*, 2022, doi: 10.5220/0011300100003271.
8. M. Sedláček, F. Dohnal, J. Ivan, and M. Šustr, "Possible approaches to assessing terrain mobility after the effects of artillery munition", *Cogent Social Sciences*, vol. 10, no. 1, Jun. 2024, doi: 10.1080/23311886.2024.2368096.
9. M. J. Lawrence, H. L. J. Stemberger, A. J. Zolderdo, D. P. Struthers, and S. J. Cooke, "The effects of modern war and military activities on biodiversity and the environment", *Environmental Reviews*, vol. 23, no. 4, 2015, doi: 10.1139/er-2015-0039.
10. A. Svobodová, F. Dohnal, O. Pekař, and M. Blaha, "Using Fusion of Digital Elevation Models for Artillery Crest Clearance Determination: A Study from the Czech Republic", *2025 International Conference on Military Technologies (ICMT)*, May 2025, doi: 10.1109/icmt65201.2025.11060899.
11. O. Rolenec, M. Bilina, O. Pekař, J. Drozd, and N. Gottvaldová, "Unmanned Aerial Vehicle LiDAR Scanning for Railway Security: Pre- and Post-Explosion Analysis", *2025 International Conference on Military Technologies (ICMT)*, May 2025, doi: 10.1109/icmt65201.2025.11060900.
12. N. C. Crawford, "Pentagon Fuel Use, Climate Change, and the Costs of War", Providence, 2019. Accessed: Mar. 16, 2026. [Online]. Available: https://costsofwar.watson.brown.edu/sites/default/files/papers/Crawford-Pentagon-Fuel-Use-Climate-Change.pdf
13. J. Neubauer, M. Vlkovsky, and J. Michalek, "Statistical modeling of cargo securing on selected military trucks and road surfaces", *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, vol. 21, no. 3, Jan. 2024, doi: 10.1177/15485129241227012.
14. V. Šlouf, M. Blaha, O. Pekař, L. Brizgalová, and V. Müller, "AN ALTERNATIVE MODEL FOR DETERMINING THE RATIONAL AMOUNT OF FUNDS ALLOCATED TO DEFENCE OF THE CR", *Obrana a strategie (Defence and Strategy)*, vol. 23, no. 1, Jun. 2023, doi: 10.3849/1802-7199.23.2023.01.149-172.
15. R. P. Thombs, A. K. Jorgenson, and B. Clark, "Reducing U.S. military spending could lead to substantial decreases in energy consumption", *PLOS Climate*, vol. 4, no. 7, Jul. 2025, doi: 10.1371/journal.pclm.0000569.
16. J. Novák, L. Potužák, M. Blaha, and V. Šlouf, "The Impact of the Deteriorated Political and Security Situation on the Financial Stability of Arms Companies Operating in an Oligopolistic Market Environment", *Challenges to National Defence in Contemporary Geopolitical Situation*, vol. 1, no. 1, Nov. 2024, doi: 10.3849/cndcgs.2024.500.
17. M. Blaha and K. Brabcová, "Determination of final ammunition consumption", *WSEAS Transactions on Business and Economics*, vol. 9, no. 2, 2012, doi: 10.5555/2183264.2183285.

18. M. Šustr, M. Vajda, M. Blaha, J. Ivan, and D. Korec, “Artillery officer education and the interoperability challenge in Joint fires: a Czech–Slovak comparison”, *Cogent Education*, vol. 12, no. 1, Jul. 2025, doi: 10.1080/2331186x.2025.2533308.
19. T. Havlík, M. Šustr, J. Ivan, O. Pekař, and M. Mušinka, “Evaluation of the effectiveness of a firing battery in self-defense and protection in the area of firing positions using constructive simulation”, *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, vol. 23, no. 2, Nov. 2024, doi: 10.1177/15485129241291579.
20. N. Świętochowski, J. Varecha, D. Korec, V. Vitoul, and M. Hercík, “Immersive Training of Artillery Observers with Integrated Artificial Intelligence”, *Communications in Computer and Information Science*, vol. 2026, no. 2, 2026, doi: 10.1007/978-3-032-16451-3_19.
21. S. Höhnová, M. Blaha, L. Skoruša, and M. Hercík, “Normative Analysis of the Environmental Impacts of the Artillery of the Army of the Czech Republic in the Context of Czech Law, International Law, and NATO”, Veredas do Direito, vol. 23, no. 7, 2026, doi: 10.18623/rvd.v23.4915.
22. *Approach to managing the impacts of climate change on the defence of the Czech Republic*. Praha: Ministry of Defence of the Czech Republic - MHI Prague, [2025]. Accessed: Apr. 23, 2026. [Online]. Available: https://www.mo.gov.cz/assets/en/ministry-of-defence/basic-documents/337-25_zamer-zvladani-dopadu-klimatu-na-obranu-cr---aj-_1_.pdf
23. J. Varecha and I. Majchút, “Modelling of Artillery Fire and Simulation of its Efficiency”, *International conference KNOWLEDGE-BASED ORGANIZATION*, vol. 25, no. 3, Jun. 2019, doi: 10.1515/kbo-2019-0134.
24. P. Stodola and L. Kutěj, “Multi-Depot Vehicle Routing Problem with Drones: Mathematical formulation, solution
25. algorithm and experiments”, *Expert Systems with Applications*, vol. 241, 2024, doi: 10.1016/j.eswa.2023.122483.
26. P. Zahradníček, L. Rak, and J. Zezula, “Budoucí prostředí a robotické autonomní systémy”, Vojenské rozhledy, 2022, doi: 10.52651/vr.a.2022.2.56-72.
27. J. Nohel, P. Stodola, Z. Flasar, D. Kristalova, P. Zahradnicek, and L. Rak, “Swarm Maneuver of Combat UGVs on the Future Digital Battlefield”, in Lecture Notes in Computer Science, Cham: Springer International Publishing, 2023, pp. 209–230, doi: 10.1007/978-3-031-31268-7_12.
28. J. Drozd, L. Rak, P. Zahradnicek, P. Stodola, and J. Hodicky, “Effectiveness Evaluation of Aerial Reconnaissance in Battalion Force Protection Operation Using the Constructive Simulation”, The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, vol. 20, no. 2, pp. 181–196, 2021, doi: 10.1177/15485129211040373.
29. M. Kratky, V. Minarik, M. Sustr, and J. Ivan, “Electronic Warfare Methods Combatting UAVs”, Advances in Science, Technology and Engineering Systems Journal, vol. 5, no. 6, pp. 447–454, 2020, doi: 10.25046/aj050653.
30. J. Šotnar, L. Potužák, and O. Pekař, “Analýza metod určování polohy bodů v prostředí bez dostupnosti GNSS”, Vojenské rozhledy, 2025, doi: 10.52651/vr.a.2025.2.23-38.
31. D. Sládek, M. Šustr, J. Ivan, and F. Hudec, “Building Meteorological Backup Artillery Products: Leveraging Upper Air Data”, Vojenské rozhledy, vol. 34, no. 1, pp. 136–158, 2025, doi: 10.3849/2336-2995.34.2025.01.136-158.
32. J. Drábek, M. Šustr, L. Potužák, J. Ivan, and R. Liška, “Contingency and Emergency Manual Procedures for Calculation Firing Data Using Direction and Distance Coefficients”, Engineering Reports, vol. 7, no. 6, 2025, doi: 10.1002/eng2.70252.
33. K. Hasilová, I. Horová, D. Valis, and S. Zamecnik, “A comprehensive exploration of complete cross-validation for circular data”, Statistics in Transition New Series, vol. 25, no. 3, pp. 1–12, 2024, doi: 10.59170/stattrans-2024-024.
34. K. Hasilová and D. Valis, “Reliability Estimation of Critical Infrastructure Segment Backed up by the Circular Data Analysis”, in 2023 International Conference on Military Technologies (ICMT), IEEE, 2023, pp. 1–7, doi: 10.1109/icmt58149.2023.10171311.
35. D. Cimr, H. Tomaskova, R. Cimler, J. Kuhnova, and V. Slouf, “A System to Evaluate an Air-Strike Threat Level Using Fuzzy Methods”, in Lecture Notes in Computer Science, Cham: Springer International Publishing, 2018, pp. 322–331, doi: 10.1007/978-3-319-98446-9_30.
36. M. Syc, J. Vyravsky, H. Muniz Sierra, E. Korotenko, and P. Kamenikova, “Resource Recovery Potential of Incineration Bottom Ash Fine Fraction”, Waste Management, vol. 190, pp. 569–577, 2024, doi: 10.1016/j.wasman.2024.10.020.
37. V. Hujer, V. Šlouf, and J. Farlík, “Utility as a Key Criterion of a Decision-Making on Structure of the Ground Based Air Defence”, in Lecture Notes in Computer Science, Cham: Springer International Publishing, 2022, pp. 249–260, doi: 10.1007/978-3-030-98260-7_15.
38. M. Švehlík, M. Sedláček, K. Hasilová, J. Drábek, and V. Šlouf, “Applications in Engineer and Artillery Support: Mathematical Modeling of Sympathetic Detonation”, Challenges to National Defence in Contemporary Geopolitical Situation, vol. 1, no. 1, 2024, doi: 10.3849/cndcgs.2024.634.
39. M. Švehlík, M. Šustr, L. Potužák, J. Varecha, and J. Drábek, “Creating of Minefield Breaches with Artillery”, in Proceedings of the 20th International Conference on Informatics in Control, Automation and Robotics, SCITEPRESS – Science and Technology Publications, 2023, pp. 266–272, doi: 10.5220/0012208500003543.

40. T. Palasiewicz, O. Rolenec, L. Kroupa, P. Manas, and D. Coufal, “Blast-Induced Deformations of the Building Entrance Part Caused by Improvised Shaped Charges”, in Lecture Notes in Computer Science, Cham: Springer International Publishing, 2023, pp. 109–130, doi: 10.1007/978-3-031-31268-7_7.
41. M. Polach and M. Vlkovsky, “Resilience of the Railway Infrastructure in an Urban Agglomeration with Regard to the Transport of Specific Material”, in 2023 Smart City Symposium Prague (SCSP), IEEE, 2023, pp. 1–8, doi: 10.1109/scsp58044.2023.10146118.
42. M. Vlkovsky, R. Kutil, K. Bednar, and J. Kotisa, “The influence of truck mileage on cargo securing”, in AIP Conference Proceedings, vol. 2990, AIP Publishing, 2023, doi: 10.1063/5.0171303.
43. J. Černý and J. Pitaš, “Analýza variant vlastní činnosti v plánovacím a rozhodovacím procesu s využitím válečné hry”, Vojenské rozhledy, 2024, doi: 10.52651/vr.a.2024.1.37-54.
44. M. Blaha, J. Varecha, J. Drábek, and J. Novák, “Comparison of AI Speech-to-Text Systems and Their Application in Artillery Command and Fire Control Systems”, in Communications in Computer and Information Science, Cham: Springer Nature Switzerland, 2025, pp. 82–95, doi: 10.1007/978-3-032-04339-9_6.
45. M. Krátký, O. Pekař, and J. Ivan, “Simulation Support of Teaching and Research Activities at the Departments of Combat Support Forces at the University of Defence”, in 2023 International Conference on Military Technologies (ICMT), IEEE, 2023, pp. 1–8, doi: 10.1109/icmt58149.2023.10171204.
46. O. Pekař, V. Šlouf, J. Šotnar, L. Potužák, and T. Havlík, “War Game as a Method of Training, as a Method of Analysis”, European Conference on Games Based Learning, vol. 16, no. 1, pp. 651–654, 2022, doi: 10.34190/ecgbl.16.1.656.
47. D. Korec, M. Blaha, J. Barta, and J. Varecha, “Innovative Approaches to the Use of Artillery in Wildfire Suppression”, Fire, vol. 8, no. 6, p. 232, 2025, doi: 10.3390/fire8060232.