


# The war exposome: Environmental, chemical, and psychosocial determinants of health

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## Abstract

Armed conflict profoundly reshapes human exposure environments by generating intense and heterogeneous combinations of chemical, physical, biological, and psychosocial stressors. These exposures do not occur in isolation but interact dynamically across the life course, potentially influencing biological systems, disease risk, and population health in complex and insufficiently understood ways. While growing evidence documents war-related environmental contamination and mental health impacts, their cumulative and integrative biological consequences remain inadequately conceptualized within existing environmental health frameworks. This perspective introduces the concept of the war exposome as a unifying framework to capture the totality of exposures generated or intensified by armed conflict. War-related exposures are characterized by high intensity, temporal compression, spatial heterogeneity, and frequent coincidence with sensitive developmental and biological windows. Environmental degradation, uncontrolled combustion, infrastructure damage, and disrupted water and sanitation systems generate complex mixtures of chemical and physical hazards, including heavy metals, disinfection by-products, persistent pollutants, and microplastics. These hazards interact with chronic psychosocial stress, trauma, displacement, and behavioral disruption, shaping biological vulnerability through shared pathways such as immune dysregulation, oxidative stress, endocrine perturbation, and epigenetic modification. We outline a war-adapted exposome research framework integrating environmental mapping, human biomonitoring, psychosocial assessment, and data integration using exposome-oriented analytical approaches, while addressing ethical, logistical, and data-governance challenges specific to conflict settings. Conceptualizing armed conflict through an exposome lens may advance interdisciplinary research, inform humanitarian health surveillance, and support evidence-based post-conflict recovery and reconstruction strategies.

**Key words:** war exposome; armed conflict; human biomonitoring; post-conflict recovery.

## Introduction

The exposome concept provides an integrative framework for understanding how the totality of environmental, chemical, biological, and psychosocial exposures across the life course shapes human health and disease risk, including in contexts of extreme and prolonged stress.<sup>1-3</sup>

Armed conflict profoundly reshapes human exposure environments, generating complex and interacting biological, chemical, physical, and psychosocial stressors.<sup>4,5</sup> In Ukraine, the ongoing war has resulted in large-scale population displacement, environmental contamination, infrastructure destruction, chronic psychological stress, and disruptions to healthcare and social systems. Together, these factors create exposure patterns that are intense, heterogeneous, and highly dynamic, posing substantial challenges for conventional approaches to environmental health assessment.<sup>6,7</sup>

The exposome framework provides a comprehensive approach to capturing these complex exposure realities. As defined by the Banbury Consensus and subsequent work published in *Science*, the exposome encompasses the totality of environmental exposures—from conception onward—including chemical,

physical, biological, and social influences, as well as their biological embedding and interactions over time. Unlike traditional environmental risk assessment, which often focuses on isolated agents or short-term exposure events, the exposome emphasizes cumulative exposure, mixtures, non-chemical stressors, and their integration with biological responses across the life course.

War-related exposures represent a distinctive and understudied manifestation of the exposome. Rather than gradual accumulation, armed conflict often produces high-intensity, time-compressed exposure windows, during which individuals experience simultaneous environmental contamination, psychosocial trauma, nutritional disruption, infectious risks, and barriers to medical care. The biological meaning of such exposure windows varies substantially by age and developmental stage: for a young child or fetus, a two-year period of armed conflict may constitute a critical portion of their entire life-course exposome, whereas for an adult it may represent an acute but biologically consequential perturbation with long-term consequences.

In this context, the concept of a *war exposome* offers a useful integrative framework. It captures not only direct chemical and physical hazards—such as air and water contamination, heavy metals, combustion products, and infrastructural damage—but

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also psychosocial stress, displacement, social fragmentation, and chronic uncertainty. These exposures interact biologically through stress-response pathways, immune modulation, endocrine disruption, and epigenetic mechanisms, contributing to both immediate and delayed health effects.

Studying the exposome in conflict settings presents substantial methodological and ethical challenges. Continuous monitoring is often infeasible, and data collection must rely on opportunistic sampling, portable monitoring technologies, remote sensing, harmonized questionnaires, and retrospective exposure reconstruction. At the same time, long-term and intergenerational follow-up is essential, as many health consequences—particularly for children, pregnant women, and other vulnerable populations—may emerge years or decades after the cessation of hostilities. Ethical considerations, including participant safety, confidentiality, and data governance, are therefore central to any exposome-oriented research in war-affected populations.

This perspective article proposes a conceptual framework for understanding and studying the war-related exposome in Ukraine.<sup>8,9</sup> Rather than serving as a purely academic exercise, the framework is intended to inform real-world environmental monitoring, humanitarian health surveillance, and post-conflict recovery planning. By situating war within the exposome paradigm, we aim to support more integrated, biologically meaningful, and policy-relevant approaches to protecting population health in conflict-affected settings.

## Defining the war exposome

The war exposome can be defined as the totality of environmental, physical, chemical, biological, and psychosocial exposures generated or intensified by armed conflict, together with their biological embedding and interactions over time. Unlike conventional environmental exposure scenarios, war-related exposures are characterized by high intensity, rapid onset, spatial heterogeneity, and temporal compression, often coinciding with critical developmental and life-course windows. These exposure constellations shape disease susceptibility, biological aging, and long-term health trajectories.<sup>8</sup>

Importantly, the war exposome extends far beyond direct physical injuries or acute toxic exposures. It encompasses sustained alterations in air, water, soil, food systems, housing conditions, social structures, and psychological environments, frequently occurring under conditions of disrupted healthcare access and limited environmental monitoring.

Within this framework, three interrelated and interacting domains of the war exposome can be distinguished:

### 1. Environmental–chemical domain.

This domain includes chemical contamination arising from damaged industrial facilities, fuel depots, military activities, uncontrolled combustion processes, and the destruction of water and sanitation infrastructure. Documented exposures include heavy metals, polycyclic aromatic hydrocarbons, volatile organohalogenes, combustion by-products, and disinfection by-products in drinking water systems. In post-conflict and frontline settings, elevated concentrations of compounds such as trihalomethanes represent a neglected but biologically relevant exposure pathway.<sup>10</sup> In Ukraine, newly characterized wartime emission sources—such as particulate matter generated by trench candles—illustrate how improvised military and

civilian practices generate complex exposure mixtures with potential respiratory, cardiovascular, and systemic effects.<sup>11</sup>

### 2. Physical–structural domain.

This domain encompasses non-chemical physical exposures and degradations of the built environment, including particulate matter from the combustion of mixed materials (“war dust”), indoor air pollution from makeshift heating and cooking sources, noise, vibration, and thermal stress, as well as the deterioration of housing and urban infrastructure. These exposures combine well-known toxicants such as benzene, PAHs, and heavy metals with emerging contaminants, including microplastic particles, reflecting the material complexity of modern urban warfare.<sup>12–14</sup>

### 3. Psychosocial–behavioral domain.

Chronic psychological stress, trauma, forced displacement, disrupted sleep, food insecurity, social fragmentation, and changes in health-related behaviors constitute central non-chemical components of the war exposome. These stressors exert profound effects on neuroendocrine regulation, immune function, and metabolic homeostasis, and can substantially modify individual vulnerability to chemical and physical hazards.<sup>15,16</sup>

## Environmental and psychosocial pathways

Armed conflicts alter nearly every layer of the exposome. The destruction of infrastructure and uncontrolled combustion of civilian and military materials generate complex mixtures of airborne and waterborne contaminants. These can already affect the global climate.<sup>17</sup> These mixtures often include polycyclic aromatic hydrocarbons, volatile organohalogenes, heavy metals, and microplastic particles. The lack of environmental monitoring during hostilities leads to large uncertainties in exposure assessment, while population displacement and loss of documentation hinder longitudinal follow-up.<sup>18–20</sup> At the same time, war transforms psychosocial and behavioral determinants of health. Chronic insecurity, forced migration, and exposure to violence trigger prolonged activation of stress pathways, with measurable effects on immune surveillance, inflammation, and metabolic regulation. Psychosocial stressors can act as effect modifiers—altering the dose-response relationships of environmental toxicants and influencing susceptibility to cancer, cardiovascular disease, and mental disorders.

Emerging evidence suggests that combined chemical and psychosocial exposures may produce additive or synergistic biological effects, mediated through shared mechanisms such as oxidative stress, epigenetic reprogramming, mitochondrial dysfunction, and neuroendocrine dysregulation. The war exposome therefore represents an extreme manifestation of multi-exposure interaction, in which chemical and non-chemical stressors converge on vulnerable biological systems across the life course.<sup>21</sup>

## A war-adapted exposome research framework

To advance the study of the war exposome, an integrative research framework is required—one that unites environmental monitoring, biological assessment, and social data under a common analytical architecture.<sup>22</sup> Such a framework can be structured around four complementary pillars:

1. Environmental mapping. Deployment of portable sensors, satellite data, and non-targeted analytical chemistry (e.g., high-resolution mass spectrometry) to detect and map pollutants in air, water, and soil.<sup>23</sup>
2. Human biomonitoring. Collection of biospecimens (blood, urine, hair, placenta, breast milk) from conflict-affected populations, focusing on biomarkers of exposure, effect, and susceptibility.<sup>24</sup>
3. Psychosocial and behavioral assessment. Integration of validated stress, trauma, and resilience metrics, allowing evaluation of non-chemical exposures alongside environmental data.<sup>25</sup>
4. Data integration and modeling. Use of exposome-wide association studies (ExWAS), mixture modeling, and machine-learning approaches to identify multi-exposure patterns and their links to health outcomes.<sup>26</sup>

Each pillar can function independently but gains substantially in interpretative power when harmonized through shared meta-data standards, time-aligned sampling strategies, and interoperable data infrastructures. A life-course perspective is central to this framework, recognizing that the biological impact of war-related exposures often extends far beyond the acute phase of conflict, influencing reproductive outcomes, child development, and aging processes.

Although large prospective cohorts may be difficult to establish during active hostilities, the creation of smaller longitudinal or hybrid cohorts—including post-conflict follow-up—is essential for capturing delayed and intergenerational health effects. International collaboration, open science principles, and FAIR data practices will be critical for ensuring reproducibility, comparability, and the long-term scientific value of exposome research conducted in war-affected settings (Figure 1).

## Ethical and data considerations

Exposome research in war and post-conflict settings raises distinct ethical, logistical, and data-governance challenges that extend beyond those encountered in conventional environmental health studies. Armed conflict introduces heightened risks related to participant safety, population displacement, political sensitivity, and long-term vulnerability, requiring ethics frameworks that are both robust and context-adaptive.

The collection of environmental samples and human biospecimens must adhere to international standards for human-

subject protection, informed consent, and data confidentiality, even when healthcare systems, legal oversight, and digital infrastructure are partially disrupted. In war-affected populations, informed consent procedures may need to be simplified, iterative, or mediated through trusted local institutions, while ensuring that participation does not expose individuals or communities to additional risk. Particular care is required to avoid stigmatization, misinterpretation of findings, or perceptions of “extractive” research that benefits external actors without tangible local return.

Data governance represents a central challenge for war-exposome research. While the exposome field increasingly emphasizes open science and FAIR (Findable, Accessible, Interoperable, Reusable) data principles, unrestricted data sharing may be inappropriate in conflict settings. Sensitive geospatial, biological, or health-related data can pose security risks if improperly disclosed.<sup>27</sup> Accordingly, FAIR principles must be operationalized through controlled-access models, tiered data-sharing agreements, encrypted storage, and clear governance structures that define who can access data, under what conditions, and for what purposes.

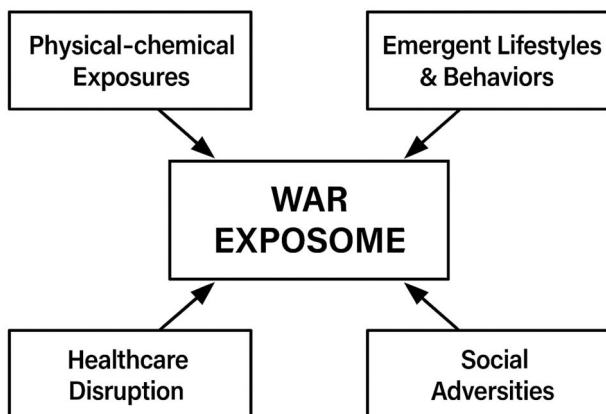
Embedding data sovereignty and ethics-by-design principles within war-exposome studies is essential to maintain trust and ensure long-term scientific and societal value. This includes transparent benefit-sharing arrangements, capacity building for local researchers and institutions, and mechanisms that allow affected communities to retain agency over how their data are used during and after conflict. Simplified and harmonized meta-data frameworks may facilitate the secure integration of war-related datasets into global exposome platforms without compromising participant protection.

Experience from previous disaster and conflict-related research—including environmental health monitoring following the Fukushima nuclear accident and biomonitoring studies conducted after the Gulf War—demonstrates that high ethical and methodological standards can be maintained even under severely constrained conditions. These precedents provide important guidance for the development of ethically grounded, scientifically rigorous war-exposome initiatives capable of informing both immediate humanitarian responses and long-term post-conflict recovery efforts.<sup>28,29</sup>

## Limitations

This perspective is subject to several important limitations that reflect the intrinsic challenges of conducting exposome research in active war and post-conflict settings. First, ongoing hostilities and infrastructural disruption preclude comprehensive and continuous environmental monitoring, resulting in unavoidable gaps and spatial heterogeneity in the characterization of the Ukrainian war exposome. Such data incompleteness is not a methodological flaw but a defining feature of exposure assessment under conflict conditions.

Second, restricted access to frontline and occupied territories limits the representativeness of available environmental measurements and biomonitoring samples. As a result, existing data are necessarily opportunistic and may underrepresent the most heavily affected populations. Third, the conceptual framework proposed here has not yet been validated through large-scale prospective studies. Robust empirical testing will require the restoration of stable research infrastructure, long-term funding, and sustained international collaboration, which are unlikely to be fully achievable during active hostilities.



**Figure 1.** Conceptual framework for the war exposome .

These limitations underscore the need for adaptive, flexible, and scalable exposome research strategies capable of operating under uncertainty, rather than detracting from the relevance of the war exposome framework.

## Policy and public health implications

Understanding the war exposome is not solely a scientific exercise; it is a foundation for evidence-based recovery and health protection. Environmental restoration, safe water supply, and waste management are integral to post-conflict reconstruction but are rarely guided by systematic exposure data. Integrating exposome-based monitoring into humanitarian and public health programs could help identify hidden health risks and set priorities for remediation. For instance, reports of elevated levels of disinfection by-products in drinking water systems damaged by shelling highlight the need for rapid, low-cost chemical screening. Similarly, the detection of microplastics in human tissues underscores the persistence of conflict-related pollutants across biological barriers. These examples illustrate how targeted exposome-based surveillance could support both emergency response and long-term resilience planning. Policymakers should recognize that environmental degradation and psychosocial stress are inseparable determinants of health during and after war.

In this context, the war exposome framework offers a unifying approach to integrate environmental, biological, and psychosocial data into actionable public health strategies that extend from emergency response to long-term resilience building.<sup>30,31</sup>

In this respect, the war exposome framework aligns with and complements ongoing international efforts to advance exposome science at a global scale. Recent initiatives led by the U.S. National Institutes of Health, including discovery-driven programs coordinated through the National Institute of Environmental Health Sciences, emphasize the integration of environmental exposures, lifestyle factors, and biological responses across diverse populations. In parallel, international research networks such as the Exposomics Consortium and large-scale European coordination actions under Horizon Europe reflect a growing consensus on the need for harmonized, interdisciplinary, and data-integrative exposome research. Embedding war-related exposome studies within these established frameworks offers a pragmatic pathway to ensure methodological rigor, comparability, and long-term sustainability, while enabling conflict-affected regions to contribute meaningfully to—and benefit from—global exposome research infrastructures.<sup>32-34</sup>

## Conclusions and research agenda

The human exposome is undergoing profound transformations driven by climate change, industrialization, urbanization, and large-scale environmental degradation. Armed conflict represents an extreme and accelerated manifestation of these processes, producing highly compressed and heterogeneous exposure scenarios with lasting biological consequences.

The concept of the war exposome offers a unifying framework for understanding how chemical, physical, biological, and psychosocial stressors generated by armed conflict interact to shape risks for chronic disease, adverse developmental outcomes, and accelerated biological aging at the population level. Addressing this complexity requires close interdisciplinary collaboration among environmental scientists, clinicians, epidemiologists,

toxicologists, social scientists, and data specialists, as well as sustained engagement with affected communities.

Informed by current knowledge gaps and methodological constraints, several research priorities emerge for the coming decade. These include:

1. developing standardized and context-adapted protocols for sampling, characterizing, and interpreting complex environmental mixtures in conflict and post-conflict settings;
2. establishing pilot biobanks and longitudinal or hybrid cohorts capable of capturing delayed, cumulative, and potentially transgenerational health outcomes;
3. systematically integrating psychosocial indicators with biological and chemical markers within unified exposome databases;
4. applying high-resolution, non-targeted analytical approaches, including mass spectrometry-based exposomics and metabolomics, to identify novel exposure signatures associated with war-related environments;
5. establishing ethical, secure, and interoperable data infrastructures that are FAIR-compliant and compatible with global exposome research consortia.

Advancing this research agenda will require sustained international collaboration, long-term investment, and targeted capacity building in conflict-affected regions. Beyond its scientific value, the study of the war exposome carries a broader responsibility: to ensure the systematic measurement, scientific understanding, and eventual mitigation of the environmental and biological consequences of armed conflict. In this sense, exposing war is not only an analytical task, but also a moral imperative—to document how violence becomes biologically embedded and to inform pathways toward recovery, prevention, and long-term resilience.

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## Author contributions

Olexiy Kovalyov (Conceptualization [Equal], Formal analysis [Equal], Methodology [Equal], Project administration [Equal], Validation [Equal], Writing—original draft [Equal], Writing—review & editing [Equal]).

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## Ethics statement

This article is a conceptual Perspective and does not report original research involving human participants or animals.

## Conflict of interest

The authors declare no conflicts of interest.

## Ethical approval

Ethical approval was not required.

## Data availability

No new data were generated or analyzed in this study. Data sharing is therefore not applicable.

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