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Nature in the Crossfire: Unveiling Environmental Destruction in Warfare Through Generative AI-Assisted Assessment

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Abstract

Warfare inflicts profound ecological damage that undermines global sustainability, yet the environmental costs of conflict remain critically under-assessed due to fragmented and impractical evaluation frameworks. This study presents a novel AI-powered assessment model that integrates the Driver-Pressure-State-Impact-Response (DPSIR) framework with generative AI, satellite data, and expert validation to systematically quantify ecological impacts in conflict zones. The model enables scalable, real-time evaluations of both immediate effects—such as deforestation and chemical spills—and latent risks like groundwater contamination, even in hazardous or inaccessible areas. By providing scientifically rigorous and actionable insights, this framework empowers policymakers to prioritize ecological restoration, strengthen environmental accountability, and integrate nature-based recovery strategies into post-conflict rebuilding. Positioned at the nexus of environmental science, artificial intelligence, and international governance, this work advances a transformative approach to address conflict-driven environmental degradation, aligning recovery efforts with global sustainability goals and fostering a resilient, equitable future.

1. Introduction

Warfare devastates more than just lives, infrastructure, and governments—it silently ravages ecosystems, leaving behind environmental destruction that is often invisible, unmeasured, and unaddressed. While every human casualty and displaced individual is meticulously recorded, nature's losses—rivers poisoned, forests burned, soil rendered infertile—remain in the shadows. Bombed cities leak untreated sewage into water systems, oil spills contaminate agricultural lands, and forests, once critical carbon sinks, are obliterated, accelerating climate change and biodiversity loss (Lawrence et al., 2015). These underreported damages compound the suffering of war-torn communities, persisting long after conflicts end and undermining recovery efforts to rebuild livelihoods and ecosystems.

Take, for instance, the deforestation driven by mineral exploitation in the Democratic Republic of Congo, which destabilizes ecosystems and displaces indigenous populations. In Syria, bombings of industrial facilities have released toxic chemicals into rivers and groundwater, contaminating vital resources (Kitowski et al., 2023). In Iraq, deliberate oil refinery fires have poisoned the air, worsening respiratory diseases in already vulnerable populations (Rawtani et al., 2022). The destruction of the Kakhovka Dam in Ukraine offers a recent, stark reminder of how warfare amplifies ecological crises with catastrophic consequences (Stakhiv & Demydenko, 2023). Together, these examples underscore a critical gap: while the human cost of war is extensively quantified, the environmental toll remains poorly documented, limiting recovery efforts and policy responses.

Despite growing recognition of this issue, existing environmental assessment frameworks are fragmented and impractical in conflict zones, where access is dangerous and data collection is limited (Pereira et al., 2022). Traditional methods fail to capture both the immediate impacts—such as chemical spills and deforestation—and the latent risks, like soil degradation and groundwater contamination, that

emerge years later (Chang & Kidman, 2023; Zhu et al., 2023). Addressing this challenge is vital for achieving global sustainability goals, particularly SDG 13 (Climate Action), SDG 15 (Life on Land), and SDG 16 (Peace, Justice, and Strong Institutions).

To fill this gap, we introduce a novel AI-enhanced environmental damage assessment framework that leverages the Driver-Pressure-State-Impact-Response (DPSIR) model, enhanced to address conflict-specific environmental challenges (Masó et al., 2019). By integrating generative AI, satellite imagery, sensor data, environmental modeling, and expert validation, this interdisciplinary framework enables rapid, scalable, and remote assessments of ecological impacts across four core domains: air, water, soil, and radiation. It bridges environmental science, artificial intelligence, and international governance to provide actionable insights for policymakers, prioritizing environmental remediation strategies and informing sustainable recovery efforts (Carnohan et al., 2023; Gari et al., 2015).

Aligned with international mechanisms, such as the UN reparations framework and the European Union Directive 2004/35/CE, our framework ensures that ecological harm receives the same analytical rigor as human and infrastructure losses (Austin & Bruch, 2000; Topluoglu et al., 2023). By transforming fragmented documentation into structured, evidence-based assessments, this research equips decision-makers with the tools to restore ecosystems, seek accountability, and promote resilience in conflict-affected regions.

By quantifying ecological losses, alongside human casualties, our research transforms how the world views the environmental costs of conflict. It ensures that nature is no longer the silent victim—providing the tools needed to secure justice for ecosystems and communities. This framework equips decision-makers with the scientific evidence required to act decisively, building the foundations for a more sustainable, just, and resilient post-conflict world.

2. Methods

2.1 Novel Application of Generative AI

This study is grounded in the innovative use of ChatGPT 4.0, a state-of-the-art generative AI designed to replicate the expertise of an environmental impact assessor. Tasked with generating a comprehensive list of indicators, ChatGPT played a crucial role in developing indicators to assess the ecological impacts of warfare across four core areas: air, water, soil, and radiation. In addition to identifying these indicators, the AI provided the rationale behind their selection, defined measurement units, and proposed methods for their application in conflict zones (see supplementary material for details).

This novel use of AIenabled the creation of a structured and flexible framework for assessing environmental damage. With AI's involvement, this task is highly challenging and time-consuming. The combination of AI’s systematic approach and subsequent expert refinement highlights the transformative potential of generative AI in advancing environmental research (e.g., Anderson et al., 2023; Zhu et al., 2023; Chang & Kidman, 2023; Berthelot et al., 2024).

2.2 Expert Review and Iteration

To guarantee the accuracy and applicability of the AI-generated indicators, the authors—experts in environmental impact assessment—undertook a rigorous review of ChatGPT's output. Their critical feedback and recommendations were essential in refining and enhancing the list of indicators. This iterative collaboration between the expert panel and the AI model enriched the dataset with detailed descriptive information for each indicator, ensuring it was relevant and reliable for assessing ecological damage in conflict zones. Multiple rounds of revision were conducted, resulting in a comprehensive, high-quality framework tailored to real-world applications in war-affected environments. This approach is inspired by studies where experts determine important scientific questions by ranking topics and ideas (Sutherland et al., 2006; Pretty et al., 2010; Sutherland et al., 2012).

2.3 Indicator Selection and Finalization

The objective was to identify key state-change indicators that best reflect the impact of conflict on the environment, with the long-term goal of developing universal standards for assessing environmental damage in conflict zones (European Environment Agency, 1999). The study follows the DPSIR (Driving forces, Pressures, State, Impact, Response) model (Fig. 1), which provides a widely recognized framework for evaluating environmental damage (Gari et al., 2015; Carnohan et al., 2023).

This approach allows for flexibility in selecting the most appropriate indicators depending on the specific conditions and the challenges of a conflict zone. By offering a comprehensive, expert-verified database of indicators across air, water, soil, and radiation categories, users—including policymakers, environmental agencies, and humanitarian organizations—can choose the most relevant indicators for their context (Bowring, 2024). This ensures that the framework can be effectively adapted to different regions and situations, helping to guide management and mitigation strategies based on the most significant environmental factors in each conflict area.

The availability of this adaptable framework enables a more tailored and accurate assessment of environmental damage, enhancing decision-maker’s ability to prioritize responses and implement effective remediation strategies in conflict-affected areas.

3. Conceptual Approach to the Database Development

A conceptual approach has been designed to develop an expert-validated database of state-change indicators for assessing impacts on air, water, soil, and radiation. Figure 1 illustrates a schematic diagram of the flexible and efficient conceptual approach and a tool for tailored environmental assessments in conflict zones. **The developed indicator database is accessible in the supplementary materials**.

3.1 Key Features of the Database:

1. **Structured Indicators**: The database is organized into four main environmental domains: air, water, soil, and radiation. Each category includes a curated set of indicators that reflect significant environmental changes in conflict-affected areas.
2. **Contextual Adaptability**: Users can select specific indicators that best suit the environmental and conflict conditions of the study area. This allows for precise identification of environmental damage based on deviations in multiple key indicators from their baseline values.

3.2 How to Use the Database:

1. Indicator Selection:

- Identify the primary environmental concern (e.g., air, water, and soil contaminants).
- Select the most relevant indicators from the database that align with the conflict zone's characteristics.
- Prioritize indicators based on a comparison with baseline data and the potential health or ecological risks they pose.

2. Data Acquisition:

- Analyze **remote sensing results**, such as satellite imagery and drone surveillance. These methods provide cost-effective, secure, and non-intrusive data collection. They are highly recommended due to their ability to cover large areas, minimize human risk, and maintain data accuracy in hazardous environments.
- Use publicly available satellite data (e.g., NASA's Landsat series and PACE, ESA's Sentinels) to monitor changes in vegetation cover, water quality, soil disturbances, and radiation hotspots.
- Initialize recognized and recommended environmental modeling systems (if input data are available) to assess changes in key indicators over broader spatial and temporal scales.

3. Applying the DPSIR Model:

- Integrate the selected indicators into the DPSIR model for a systematic environmental damage assessment.
- To identify significant environmental impacts, use a context-driven approach: consider environmental damage confirmed if at least three state-change indicators show substantial deviations from their baseline values.
- Use this model to trace how conflict activities influence environmental conditions and prioritize remediation efforts based on the most affected state-change indicators.

4. Establishing Baseline

- If direct baseline data is unavailable, establish proxies using similar unimpacted sites or historical data from analogous environments (Navarro-Racines et al., 2020; Amon et al., 2022; Fischer et al., 2023). This method helps distinguish between pre-existing conditions and conflict-related changes, accurately evaluating war-induced environmental damage. Using geochemical background data from these sites as proxies has proven effective in water, soil, and air assessments (Ali et al., 2024; Radočaj et al., 2024).

4. Results and Discussion

Warfare's impact extends beyond visible destruction, disrupting ecosystems and compromising the life-support systems that sustain human and non-human life (Lawrence et al., 2015; Pereira et al., 2022). Despite growing awareness of these ecological consequences, environmental damage often goes unreported or under-assessed, leaving long-term impacts unaddressed (Leal Filho et al., 2024). Previous assessments, such as those undertaken by the UN Compensation Commission after the Gulf War (Payne & Sand, 2011), highlighted the challenges of documenting ecological harm in conflict settings, often due to inconsistent methodologies and limited data access. This study's proposed framework aims to fill these gaps by offering a systematic, AI-supported approach that integrates the DPSIR (Driver-Pressure-State-Impact-Response) model with remote sensing tools, providing rapid and adaptable environmental assessments.

4.1 Strengths and Conceptual Innovation

The framework's primary strength lies in balancing scientific rigor with adaptability. Using the DPSIR model ensures a comprehensive evaluation of environmental impacts, capturing how conflict activities generate pressures on ecosystems, alter environmental states, and produce long-term consequences for both nature and public health (Gari et al., 2015; Prata, 2024). The framework also leverages generative AI, enabling the rapid identification of environmental indicators relevant to specific conflict scenarios—a feature crucial for assessments in hazardous or inaccessible areas (Anderson et al., 2023; Zhu et al., 2023).

However, conceptual limitations persist. For example, AI-generated outputs are inherently limited by their reliance on generalized knowledge, often failing to capture subtle site-specific ecological nuances. This can reduce the precision of assessments, particularly when evaluating complex ecosystem interactions, such as vegetation-soil feedback loops (Sandfort et al., 2024). Additionally, while the focus on remote sensing facilitates large-scale evaluations, it overlooks environmental changes below the surface—such as groundwater contamination—requiring complementary field-based assessments (Kitowski et al., 2023).

4.2 Shortcomings of AI-Enabled Environmental Assessment

Although the inclusion of AI introduces efficiency, it also raises concerns about the reliability and depth of environmental assessments. Generative AI models, such as ChatGPT, operate on generalized datasets

and lack the contextual awareness needed for nuanced ecological evaluations (Chang & Kidman, 2023). As a result, they may generate redundant or irrelevant indicators in specific conflict settings (Sandfort et al., 2024).

Another challenge lies in the inconsistency between indicators. Some indicators focus on straightforward variables (e.g., particulate matter concentration), while others aggregate multiple factors (e.g., ecosystem resilience), complicating cross-regional comparisons (Pereira et al., 2022). Future iterations should standardize how indicators are measured and validated to address these inconsistencies, ensuring the framework remains reliable and comparable across different conflict zones (Hellweg et al., 2023).

4.3 Challenges in Data Collection and the Risks of Proxy Baselines

Data availability remains a critical bottleneck for effective practical environmental assessments in conflict Data availability remains a critical bottleneck for effective, practical environmental assessments in conflict zones. In areas where direct baseline data is unavailable, the framework relies on proxies—such as data from ecologically similar regions—which introduces risks of misinterpretation (Navarro-Racines et al., 2020). Ecological variability between proxy regions and conflict zones can skew assessments, leading to incorrect conclusions about the extent of environmental damage (Moe et al., 2024).

Remote sensing methods, though applicable for large-scale assessments, present their limitations. Cloud cover or seasonal variations often affect satellite imagery, which can introduce observational biases (Masó et al., 2019; Zalakeviciute et al., 2022). Moreover, specific environmental impacts—such as groundwater pollution or heavy metal accumulation—remain beyond the reach of remote sensing technologies, necessitating ground-based measurements that may be logistically challenging or unsafe to conduct during ongoing conflict (Amon et al., 2022; Kitowski et al., 2023).

4.4 Legal and Policy Constraints: Aligning Science with Governance

Aligning environmental assessments with legal frameworks ensures that documented damage translates into accountability and reparations. The framework's structure aligns with international directives, such as the EU Directive 2004/35/CE on environmental liability, providing a standardized method for documenting environmental harm (European Parliament, 2004). Additionally, it supports emerging legal mechanisms, such as ecocide laws, aimed at criminalizing large-scale environmental destruction during warfare (Huang & Yi, 2023). However, discrepancies in environmental policies across regions present a challenge to achieving consistent application, potentially weakening the framework's impact.

Furthermore, the political dynamics of conflict zones may limit access to affected areas, creating gaps in environmental data. Governments or warring factions may withhold critical information, raising concerns about data integrity and transparency (Hook & Marcantonio, 2023). Addressing these challenges will

require multi-stakeholder collaboration, including environmental scientists, legal experts, and international organizations, to ensure that assessments are impartial and actionable (Pereira et al., 2022).

4.5 Systemic Bias and Ethical Considerations

Reliance on remote assessments introduces potential ethical challenges. While remote sensing offers a nonintrusive way to gather data, it may inadvertently exclude the voices and perspectives of local indigenous and marginalized communities directly impacted by environmental degradation (Sandfort et al., 2024). With community input, assessments avoid overlooking social dimensions of environmental damage, such as the loss of culturally significant landscapes or disruptions to traditional livelihoods (Amon et al., 2022).

The framework's reliance on AI models could also perpetuate systemic biases, mainly if data inputs reflect historical inequalities or regional knowledge gaps. For example, AI might generate more indicators for well-documented environmental issues (e.g., air quality) while under-representing less-studied areas, such as soil biodiversity (Sandfort et al., 2024). Future research should explore integrating local and indigenous knowledge and community-based monitoring into the framework, ensuring that environmental assessments reflect scientific and social realities.

4.6 Opportunities for Future Research and Development

The framework opens several promising avenues for future research. Integrating machine learning models for predictive analytics could enhance its ability to forecast long-term ecological changes, helping policymakers anticipate risks and take proactive measures (Radočaj et al., 2024). Developing hybrid baselining techniques—combining historical data with real-time monitoring and community observations—would further improve the accuracy and reliability of assessments (Navarro-Racines et al., 2020).

Expanding the framework to account for cumulative environmental impacts, such as the combined effects of conflict-related pollution and climate change, would also enhance its relevance in complex ecological settings. Collaboration with international organizations to create standardized global datasets could ensure consistent environmental assessments across regions, strengthening the framework's utility in conflict and post-conflict scenarios (Hellweg et al., 2023).

5. Conclusion

The framework proposed in this study provides a significant advancement in addressing the environmental consequences of warfare. Its innovative integration of the DPSIR model with AI-enabled assessments offers a practical tool for rapid and reliable environmental evaluations. However, the discussion has highlighted several critical challenges, including inconsistencies in indicator selection, data limitations, and ethical concerns. Addressing these issues will be essential for maximizing the

framework's effectiveness and ensuring that it promotes both accountability and sustainability of the ecological recovery.

Ultimately, the framework's value lies in its adaptability and interdisciplinary nature. By aligning scientific rigor with legal standards and ethical considerations, it can serve as a cornerstone for global efforts to mitigate the environmental toll of warfare. With further refinement and broader stakeholder collaboration, the framework can potentially guide more just and sustainable post-conflict recovery efforts, protecting ecosystems and the communities that depend on them.

Declarations

Author Contribution

H.J conceptualized, wrote the main manuscript, formulated figures and tables of the manuscript. All other authors had equal contributions in revising and polishing the text. Training, validating, proofing and iterating the output of AI to reach top quality standard and academic rigor.

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Data Availability

Data is provided within the supplementary information files.

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Figures

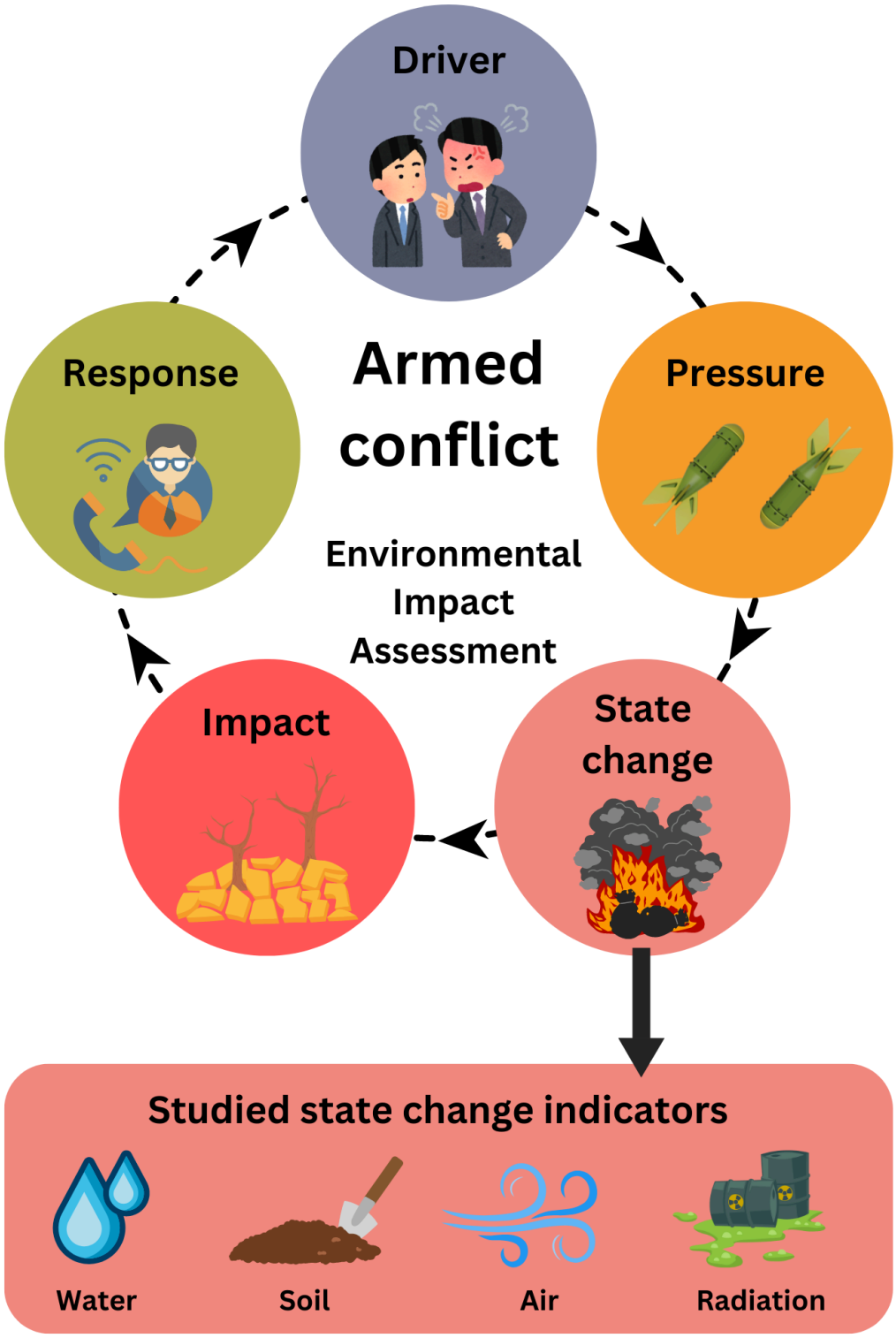


Figure 1

Illustration of a conceptual approach of the War Environmental Impact Assessment using the DPSIR Model linked to analyzed state change indicators across four broad themes: water, soil, air, and radiation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementarymaterialDatabasecreationflowchart.docx
- Conflictzoneenvironmentalindicatordatabase.xlsx