Anthropogenic degradation of local ecosystems under extreme explosive impacts: Coupled soil geochemical anomalies and aerosol forcing

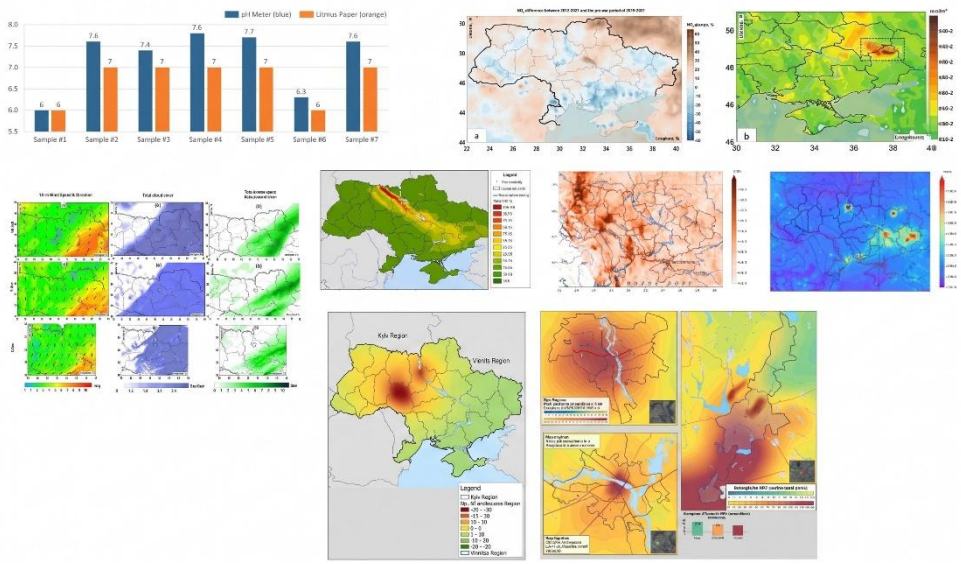
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Graphical abstract



Highlights

- Missile impacts form coupled atmospheric and soil environmental anomalies.
- Fires at fuel depots trigger acute CO and particulate matter emissions.
- XRF profiling reveals localized variations in potentially toxic elements (Ni and Cu) around impact craters.
- Concrete debris causes a critical alkaline shift (pH 7.8) in affected soils.
- The bipartite method bridges satellite monitoring and localized soil toxicity assessments.

Abstract

Extreme high-energy impacts on critical infrastructure generate unprecedented spatially coupled environmental anomalies. Traditional approaches to assessing technogenic hazards often consider soil degradation and atmospheric pollution as separate processes, which reduces the effectiveness of spatial planning for emergency response.

The aim of this study is to quantitatively assess a coupled two-phase environmental anomaly caused by missile strikes in order to develop strategies for ensuring environmental safety and reducing disaster risk. An integrated two-level design was applied: a macroscale analysis of the acute atmospheric phase, based on Sentinel-5P/TROPOMI satellite monitoring and SILAM numerical dispersion modeling using 40,000 cores on the PUHTI supercomputer, was combined with targeted microscale profiling of the chronic pedological phase using XRF spectrometry along a high-resolution transect across the epicenter of an X-101 missile crater.

It was established that the destruction of infrastructure generates extreme emission pulses, with CO increasing by up to 362.5% and SO_2 by up to 454.8%, as well as aerosol forcing that locally triggers extreme precipitation. At ground level, a persistent geochemical gradient was identified, characterized by local accumulation of potentially toxic elements (e.g., Sr up to 184 mg/kg and Cu with an anthropogenic enrichment factor of 2.6) and a critical shift in acid-base balance toward alkalinity, with pH reaching 7.8. The study demonstrates that high-energy explosions act as a systemic trigger of complex environmental degradation. The proposed methodology provides an objective scientific basis for spatially targeted reclamation and emergency risk management strategies.

Keywords: conflict-related soil contamination; explosive ordnance; potentially toxic elements; portable XRF; Sentinel-5P/TROPOMI; SILAM dispersion modeling; soil alkalinization; disaster risk reduction; civil protection; environmental safety.

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