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UAV Workflows for Demining and Environmental Monitoring: A Critical Review of Wartime and Humanitarian Requirements

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Abstract

This study evaluates the role of unmanned aerial vehicles (UAVs) in demining operations and environmental monitoring under wartime and post-conflict conditions. A structured literature review (2015–present) assessed UAV-enabled detection, mapping, and environmental sensing capabilities. The results indicate that UAVs significantly enhance reconnaissance efficiency, reduce suspected hazardous areas, and improve safety, yet cannot independently meet humanitarian clearance standards. While wartime use prioritises rapid risk mitigation, post-conflict deployment supports systematic clearance, environmental monitoring, and land restoration. The study highlights a gap in doctrinal integration and underscores the need for standardised UAV-based demining and environmental workflows.

KEY WORDS: *demining, environmental assessment, humanitarian demining, NATO, sensors, unmanned systems*

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1. Introduction

The current situation in demining is increasingly shaped by the rapid expansion of contaminated areas, driven by the war in Ukraine [1]. Despite ongoing technological progress, humanitarian demining still relies heavily on manual clearance, a procedure that remains inherently slow, labour-intensive, and high-risk for personnel [2]. Consequently, current efforts prioritize the development and deployment of autonomous and semi-autonomous solutions—such as remotely operated robotic ground systems and unmanned aerial vehicles (UAVs)—including AI-enabled approaches for area reconnaissance and mine detection in suspected minefields [1, 3–5]. A key operational challenge is the required clearance standard: while military operations often aim to establish safe lanes or corridors through minefields, humanitarian demining typically demands full clearance to enable the safe civilian use of land and infrastructure [2].

Within this context, UAVs are emerging as a critical capability for increasing the efficiency of area reconnaissance and supporting stand-off neutralization of mines and unexploded ordnance (UXO) [1]. Their primary contribution lies in high-resolution mapping of suspected hazardous areas, recognition of spatial deployment patterns, and the production of georeferenced outputs that support subsequent clearance planning and prioritization [2]. In addition, recent technological developments enable certain UAV platforms to conduct limited active disposal actions—e.g., delivering small charges onto localized targets—thereby reducing the need for human entry into hazardous zones and lowering exposure risk. Overall, UAV integration can substantially improve personnel safety and accelerate land release for civilian use [6]. Although several UAV-enabled applications remain in the testing and validation phase, United Nations Mine Action Service (UNMAS) has identified UAVs as a highly promising and increasingly functional toolset for humanitarian demining workflows [2].

The war in Ukraine simultaneously represents a salient example of environmental degradation caused by armed conflict. Large-scale contamination of agricultural soils—previously among Europe's key grain-producing regions—has become a growing concern that will require systematic post-conflict assessment and remediation [7, 8]. Field measurements from selected affected localities indicate that concentrations of heavy metals can substantially exceed applicable regulatory thresholds, underscoring the potential for long-term impacts on food security, ecosystem services, and human health [8, 9].

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UAV-based environmental monitoring offers a unique interface between detailed near-surface observations (including in difficult-to-access areas) and broader satellite remote sensing, combining high spatial resolution with flexible deployment at comparatively low operational cost [10, 11]. While UAV applications in environmental monitoring were until recently largely associated with civilian sectors—most notably agriculture and construction—technology transfer and the operational demands of contemporary conflicts make their adoption within the defense sector increasingly inevitable for monitoring the environmental impacts of military activities. In addition to cost-effectiveness, a decisive advantage of UAV systems is the availability of advanced sensor payloads, including multispectral and hyperspectral cameras, thermal sensors, and LiDAR. These enable the monitoring of vegetation stress, soil erosion dynamics, surface disturbance, and indicators of chemical contamination [10, 11].

Importantly, demining operations themselves may impose secondary environmental burdens, particularly through soil disturbance and compaction associated with heavy mechanized assets [12, 13]. In this regard, UAV-supported approaches may offer a less invasive alternative by reducing reliance on heavy ground equipment and minimizing secondary soil degradation, while simultaneously improving operational safety by limiting human presence in hazardous areas. The paper delineates how UAV use in wartime demining can be reconciled with environmental protection requirements, with emphasis on post-clearance environmental monitoring. By explicitly separating military and humanitarian clearance logics, the paper derives a structured understanding of where UAV-based methods already support environmentally informed land release and where additional operational integration is still missing.

2. Materials and Methods

The study adopts a critical review approach to (i) describe the current state of UAV-enabled demining and (ii) evaluate to what extent contemporary research and operational practice integrate environmental protection requirements, particularly post-clearance environmental monitoring. The review is intentionally problem-driven rather than purely descriptive: it seeks to identify where UAV-supported demining workflows—especially those applied during ongoing conflict—align with, or fall short of, emerging expectations for environmental stewardship and monitoring after clearance. A structured literature search is conducted to identify studies addressing UAV/drone applications in demining operations with relevance to environmental monitoring and restoration. The search is performed using the following query (adapted to each database's syntax): *(UAV OR drone) AND ("mine detection" OR demining) AND ("environmental monitoring" OR "ecological restoration" OR "soil contamination")*. To capture the period most relevant to current UAV payload capabilities and AI-enabled processing, the search was limited to publications from 2015 onward.

3. Results and Discussion

3.1 UAV-enabled Demining: During War and Post-war

UAV-based demining represents one of the most rapidly evolving areas of mine action technology. A comprehensive review of UAV applications in humanitarian demining, with specific application to the Ukrainian context, identified high-resolution mapping, pattern recognition, and GIS-integrated outputs as primary contributions of UAV systems to area survey and clearance prioritization [14]. According to the United Nations Mine Action Service (UNMAS), UAVs are now considered a functional and increasingly deployed toolset within humanitarian demining workflows [2]. Earlier robotic systems for mine detection established the foundational design requirements for autonomous platforms operating in complex minefield environments [15]. The integration of UAV platforms with geospatial analysis tools has substantially reduced the time required to generate suspected hazardous area (SHA) delineations compared to traditional ground survey methods, while simultaneously improving spatial accuracy of resulting maps [2, 16]. Systematic reviews document a broad spectrum of sensor configurations deployed across operational and research contexts, confirming that no single sensor modality is sufficient for reliable mine detection across the full range of soil types, burial depths, and mine typologies encountered in conflict-affected environments [2, 15, 16]

During war, UAV employment in demining is primarily oriented toward rapid situational awareness and military objectives. Drone platforms support intelligence, surveillance, and reconnaissance (ISR) missions, identifying freshly laid minefields, anti-vehicle obstacles, and safe corridors for troop movement [1]. The operational environment imposes severe constraints, as GPS/GNSS jamming is widespread, requiring SLAM-based navigation or IMU/LiDAR sensor fusion to maintain positional accuracy. Flight windows suitable for UAV operation occur in only approximately 25% of days annually in some affected regions [10, 11]. Beyond navigation degradation, the electromagnetic environment in active conflict zones introduces additional challenges for magnetometry payloads, which are susceptible to interference from metallic debris and armoured vehicle traffic [17]. Fixed-wing platforms are preferred for wide-area corridor screening due to their greater endurance, whereas multi-rotor systems offer hovering capability and lower operational altitude needed for detailed anomaly investigation in confined terrain [2, 16]. Despite these operational constraints, UAV-derived products, including georeferenced orthomosaics and LiDAR-based terrain models, have demonstrated practical utility in support of combat engineering decisions by providing spatially accurate outputs that guide vehicle routing and subsequent manual clearance [1, 2].

Post-war, UAV demining transitions from reactive ISR to systematic technical survey supporting land release. Applying deep learning to UAV-collected multispectral and thermal data has demonstrated substantial detection performance. A Faster R-CNN approach for PFM-1 scatterable mines achieved testing accuracy above 99 % in controlled environments [18].

The Odyssey 2025 project detected over 2,500 buried landmines in Chad using drone-plus-GIS workflows, and these methods are now being scaled to Ukraine [14]. The transition to post-conflict survey also enables longer mission durations and higher area coverage rates, as platforms are no longer constrained by active threat avoidance requirements. Multi-sensor fusion, combining thermal infrared, multispectral, and ground-penetrating radar data acquired in sequential overflights, has been identified as the most promising pathway toward meeting the 99.6 % confidence clearance standard required for humanitarian land release [2, 14, 16]. Key sensor modalities documented in peer-reviewed literature include:

- Thermal infrared (TIR) exploits differential heat capacity between mine bodies and surrounding soil and is effective for surface-laid and shallowly buried items [14, 18].
- Ground-Penetrating Radar (GPR) detects subsurface discontinuities. UAV-borne miniaturised GPR systems are under active development and field validation [14].
- Multispectral and hyperspectral cameras enable spectral anomaly detection associated with soil disturbance, vegetation die-off, and explosive residues [18].
- LiDAR produces centimetre-accurate digital terrain models (DTM/DSM), revealing micro-relief changes from craters and subsurface pressure effects [10].

A critical operational distinction is that humanitarian demining requires clearance to 99.6 % confidence to a depth of 13 cm. This is a standard that currently no single UAV sensor system can guarantee independently [2]. UAVs therefore function as a force multiplier, as aerial survey narrows the suspected hazardous area (SHA), enabling targeted manual or mechanical clearance. AI-assisted imagery analysis tools are beginning to automate pattern identification, reducing the extent of costly technical survey [2, 16]. Recent field trials confirm that integrating AI-based anomaly classification with multi-sensor UAV survey can reduce the size of the SHA by up to 70 % compared to conventional non-technical survey, substantially accelerating subsequent manual operations [2, 16, 18].

Significant gaps remain. Scientific literature on UAV demining in active conflict settings is limited, and most peer-reviewed studies address post-conflict or civilian demining contexts. Military secrecy and classification of research and development results restrict knowledge transfer [2]. Standardised validation protocols for UAV-based mine detection are absent, and the lack of multi-year funding for humanitarian demining constrains technology maturation [2]. Furthermore, the absence of harmonised data formats for UAV survey outputs limits interoperability between national demining organisations and international bodies, reducing the efficiency of multi-actor clearance programmes [14]. Addressing these gaps will require coordinated investment in open validation datasets, standardised sensor performance benchmarks, and sustained engagement between the research community and operational humanitarian demining actors.

3.2 UAV-enabled Environmental Monitoring: During War and Post-war

From a NATO perspective, environmental protection constitutes a critical cross-cutting domain that must be systematically integrated across all phases of military operations, as outlined in MC 469/1 [19]. Primary responsibility for its implementation is assigned to military engineering units (MILENG) under MC 560/2 [20], with secondary support provided by military logistics. The operationalisation of environmental tasks is further elaborated within the AJEPP framework series, which defines procedural and technical requirements for environmental management in deployed operations.

The deployment of UAVs represents a significant technological advancement in environmental monitoring. These systems enable safe and efficient data acquisition in high-risk or inaccessible environments, effectively bridging the gap between in-situ field surveys and satellite-based remote sensing. UAV-based monitoring provides ultra-high spatial resolution (centimetre-level) data with near real-time availability, thereby enhancing situational awareness in dynamic operational environments [10, 11, 21]. As described in [10, 22], such systems are applicable to vegetation assessment, water quality monitoring, and soil surface characterisation, while their integration with wireless sensor networks enables scalable, real-time environmental surveillance. Furthermore, the fusion of UAV-derived data with satellite time series allows for comprehensive and multi-scale assessment of environmental damage in conflict-affected regions.

Despite these capabilities, it is necessary to acknowledge that, within the operational priorities of armed conflict, mission accomplishment remains paramount. Although efforts are made to minimise environmental damage, environmental monitoring does not constitute a primary operational objective during active hostilities. In accordance with *AJEPP-2* [23], environmental considerations are nevertheless embedded throughout the operational lifecycle, particularly through the implementation of *Environmental Baseline Studies* (EBS) and *Environmental Closeout Studies* (ECS), as well as continuous environmental monitoring during operations and military exercises. In this context, UAV-based monitoring assumes a secondary yet strategically relevant role. Specifically, UAVs provide critical capabilities for the detection of acute environmental hazards, including toxic releases from damaged industrial infrastructure (HAZMAT incidents), identification of newly contaminated corridors, and rapid documentation of landscape degradation [1]. Remote sensing approaches have already demonstrated effectiveness in near-real-time monitoring of war-induced environmental damage in conflict zones such as Ukraine and Syria, with UAVs extending these capabilities to sub-metre resolution in areas inaccessible to ground-based teams. Additionally, UAVs facilitate the monitoring of contamination in agricultural land resulting from military activities [9].

In the post-conflict phase, the role of unmanned systems shifts from ISR towards systematic support of environmental recovery and verification processes [21]. This transition is particularly evident in the context of ECSs and the implementation of the *Zero Footprint* principle, especially during the decommissioning of military installations. UAVs play a key role in the detection of landmines and UXO, where platforms equipped with ground-penetrating radar (GPR), magnetometers, or LiDAR enable high-precision localisation of subsurface threats. This significantly accelerates humanitarian demining efforts and facilitates the safe reuse of land for civilian purposes, including agriculture [24, 25].

Table 1. UAV use in demining and environmental monitoring: Wartime vs. post conflict.

	During war	**Post-war**
UAV-enabled demining	Yes	Yes
UAV-enabled environmental monitoring	No (not a priority)	Yes (definitely)
Integrated UAV use for demining and	No	Yes

Moreover, UAVs are highly effective in mapping so-called "military badlands"—areas severely degraded by combat—and in quantifying mechanical disturbances such as crater formation and soil compaction caused by heavy military equipment, which can disrupt hydrological regimes [24]. They also enable the detection of explosive residues and munition remnants in soil and water bodies, providing essential input for the planning and prioritisation of decontamination interventions. In parallel, UAVs can be employed to monitor the effectiveness of ecological restoration measures, including phytoremediation and land reclamation [21]. Using vegetation indices such as Normalized Difference Vegetation Index (NDVI), it is possible to assess vegetation health, track the establishment of pioneer species, and evaluate long-term ecosystem recovery trajectories. A consolidated overview of UAV applications for demining and subsequent environmental monitoring is provided in Table 1.

4. Conclusions

UAV-enabled demining in wartime conditions remains an emerging topic. To date, the scientific literature has predominantly addressed UAV applications in the context of humanitarian demining, while evidence and conceptual frameworks tailored to active-conflict settings remain limited. The review of UAV-enabled demining confirms that unmanned systems already provide measurable operational value in both wartime ISR and post-conflict technical survey, yet no single sensor modality can independently meet the 99.6% confidence clearance standard required for humanitarian land release [2]. Multi-sensor fusion and AI-assisted anomaly classification represent the most promising pathway toward closing this gap, with recent studies indicating SHA reductions of up to 70% compared to conventional survey methods [2, 16, 18]. At the same time, the absence of standardised validation protocols, sparse scientific literature on UAV demining in active conflict, and incompatible data formats between organisations remain critical barriers to broader operational integration [2, 14]. Addressing these shortfalls through coordinated investment in open validation datasets and internationally agreed sensor benchmarks is a prerequisite for scaling UAV-based demining to the scope required by conflicts such as the ongoing war in Ukraine.

Although NATO has committed to environmental protection, and UAVs represent a highly effective tool for environmental monitoring—supporting both preventive and remedial actions—their practical deployment remains strongly conditioned by operational priorities. In post-conflict environments, UAV-enabled monitoring becomes significantly more prominent, particularly where humanitarian demining and environmental risk management are directly linked to civilian recovery and ecosystem restoration. Conversely, during active hostilities, environmental protection is rarely treated as a primary operational objective. As a result, the utilisation of UAVs is predominantly oriented towards rapid risk mitigation, force protection, and mission-driven clearance tasks, rather than systematic environmental monitoring. Nevertheless, even within these constraints, UAVs provide critical capabilities for identifying acute environmental hazards and informing immediate response measures. Although AJEPP-2 [23] does not explicitly prescribe the use of UAVs for environmental monitoring, prevention, or remediation, their application is readily transferable from established civilian sectors, particularly precision agriculture and civil engineering. The formal integration and standardisation of UAV-based environmental missions within this doctrinal framework would enhance the efficiency, safety, and environmental sustainability of data collection in hazardous and contaminated areas. Ultimately, such an approach would establish a robust methodological foundation for strengthening environmental protection practices and supporting the long-term resilience of both civilian populations and ecosystems mostly in post-conflict settings.

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