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Research Article

From War Scars to Green Shores: Prioritizing Ecological Resilience and Livelihood Integration in Post-Conflict Land Restoration

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Abstract

Post-conflict recovery is critically constrained by the pervasive environmental damage and contamination left by explosive remnants of war (ERW). This analysis synthesizes evidence establishing that ecological recovery is fundamentally limited by the speed and efficacy of humanitarian safety and risk management, creating an urgent need for an integrated approach to peacebuilding. The research identifies two critical requirements for accelerating resilient land restoration: first, the development of rapid, field deployable biosensors for the sensitive detection of explosive residues, and second, the establishment of standardized ecological assessment protocols tailored to the unique contamination and access risks of conflict zones. We conclude with a definitive policy call, urging international bodies and donor institutions to mandate the direct linkage of security and humanitarian funding streams to ecological restoration and sustainable land management initiatives. This approach frames environmental peacebuilding not as an optional addition, but as an essential, non-negotiable component of post-conflict reconstruction and the successful reintegration of livelihoods.

Global State of Landmines in 2025

Despite the international community's aspirational 2025 deadline for clearance under the Mine Ban Treaty, the global landmine crisis in 2025 is defined by a severe surge in new contamination from contemporary conflicts, resulting in tragically high civilian casualty rates particularly among children and is currently demanding a costly, decadelong humanitarian response centred on unprecedented technological innovation and sustained financial commitment. The year 2025 marks a crucial point for international mine action, coinciding with the initial clearance deadline established by states parties to the 1997 Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Antipersonnel Mines and on Their Destruction (the Ottawa Treaty). However, the global state of landmine and explosive remnants of war (ERW) contamination has taken a dangerous turn, driven by intense conflicts that have created vast, new minefields [1].

While longstanding contamination persists in nations like Cambodia, which aims for clearance by 2030 [2], and Sri Lanka, which is making steady progress [3], the defining feature of 2025 is the scale of new explosive hazards in active conflict zones.

Ukraine

Following the 2022 invasion, Ukraine is now one of the most severely mine affected countries globally, with an estimated one third of its territory contaminated by antipersonnel mines and ERW, creating a long-term obstacle to peace and recovery [4].

Gaza

Following prolonged conflict, the Gaza Strip has been widely described as an "open-air minefield" [5]. The sheer volume of unexploded ordnance (UXO) and failed munitions estimated to be 5–10% of total explosives used [6] means that clearance operations are projected to take between 20 and 30 years, significantly impeding reconstruction efforts and access to essential services [5].

Global Hotspots

Ongoing or recent fighting in Sudan and the Democratic Republic of the Congo continues to generate new ERW, compounding existing humanitarian crises [7].

The primary victims of landmines and ERW remain civilians. Recent reports consistently emphasize that the overwhelming majority of casualties, averaging around 84%, are civilians [7]. Critically, the Landmine Monitor's 2024 report highlighted that children account for approximately four out of ten of those civilian casualties, underscoring the severe and indiscriminate impact of these weapons on vulnerable populations [7,8]. The presence of UXO and landmines also severely complicates search, rescue, and recovery missions, further endangering humanitarian workers [8]. With the symbolic 2025 clearance goal missed by most contaminated states, the focus has shifted to accelerating efficiency and securing long-term funding. Clearance efforts are increasingly reliant on technological solutions:

- Innovation: New methods utilizing Artificial Intelligence (AI) and drone technology are being implemented to accelerate survey and clearance times. In Cambodia, for example, AI is successfully predicting landmine contaminated areas with high accuracy to make demining more efficient [2]. Similarly, these technologies are vital in Ukraine to mitigate the risks associated with manual searching [8].
- Funding Gap: Despite the escalating contamination, reports indicate that funding for mine action programs is decreasing [7]. This trend creates a critical gap, suggesting that without an urgent reversal in funding, the human suffering caused by ERW will continue for generations [7]. The international community recognizes the need for investment in research, development, and risk education to keep pace with the crisis [9].

The Legacy of Conflict on Land

Armed conflict leaves a multifaceted and enduring environmental legacy far exceeding the immediate physical destruction visible in battle-scarred landscapes. This degradation is defined by both overt landscape damage and a pervasive, invisible footprint of chemical contamination and land abandonment that severely hinders post-conflict recovery [10]. Establishing the true scale of this environmental toll is the first step toward effective remediation. The most tangible evidence is the physical disruption caused by "Bombturbation" the cratering, displacement, and compaction of soil from explosions and heavy military traffic [11]. For example, satellite data from recent conflicts shows the systematic destruction of agricultural land and critical tree cover, stripping the soil of its natural defenses against erosion and desertification [12]. This physical damage often leads to the displacement of communities and the subsequent abandonment of fertile land, increasing reliance on already stressed natural resources elsewhere [13].

More insidious, however, is the chemical contamination. Military actions introduce high concentrations of toxic substances into the environment, including heavy metals (such as lead, antimony, and mercury) and highly toxic energetic compounds (ECs) like 2,4,6 trinitrotoluene (TNT), RDX, and HMX [14]. When industrial sites, oil facilities, or ammunition depots are targeted, pollution events are catastrophic, generating millions of tons of debris containing hazardous materials [12]. This cocktail of physical debris and chemical toxins pollutes soil and groundwater, contributing to massive ecological degradation and subsequent health crises, as evidenced by rising rates of waterborne diseases in conflict zones [10]. These "war scars" are thus a primary obstacle to restoring both ecological function and human livelihood systems.

Effective land restoration requires differentiating post-conflict sites from landscapes impacted by industrial activity, such as postmining sites. While both involve remediation and reclamation, the primary differentiator in post-conflict zones is safety and access, driven by the presence of unexploded ordnance (UXO) and landmines [15]. In standard remediation, such as postmining reclamation, the process is governed by legal frameworks, is financially guaranteed by the operator, and follows a structured plan designed before or during extraction [16]. The main challenge is often restoring the physical landscape (e.g., contouring, soil replacement) and neutralizing acidic drainage or metal contamination. The land, though degraded, is generally safe for engineers and equipment access.

In contrast, post-conflict restoration is initially dictated by the humanitarian imperative of demining. The presence of explosive remnants of war (ERW) renders large areas inaccessible for comprehensive ecological assessment and intervention. This threat fundamentally dictates the pace and type of remediation:

a. Phased Access: Unlike mining sites, where remediation can often be a singular process, post-conflict restoration must be rigidly phased, starting with nonintrusive survey methods followed by high risk, expensive manual clearance before any significant earthmoving or ecological work can begin [15].
b. Uncertainty of Contaminant Load: The chemical contamination in conflict zones is highly localized and heterogeneously distributed based on blast sites and shrapnel dispersion, making comprehensive mapping difficult without full access.
c. Conflict Sensitive Context: Restoration must be politically and socially sensitive, often linked to peacebuilding processes, reconciliation, and the immediate need to return land to displaced populations for agricultural use [17]. This pressures planners to prioritize quick, safe access over long term, complex ecological restoration.

Therefore, the unique hurdle is that landmine and UXO clearance must be fully integrated into the ecological restoration plan, not merely treated as a prerequisite. Effective post-conflict land rehabilitation must adopt a phased, risk prioritized approach that couple's humanitarian demining efforts with ecological detoxification strategies, such as phytoremediation, to safely restore ecosystem function and secure sustainable livelihoods simultaneously.

This paper posits that a successful approach must move beyond simply clearing physical threats to actively use nature-based solutions to mitigate chemical threats. The Argument for Coupling Demining and Ecological Detoxification is fourfold.

Risk Mitigation Precedes Ecology: The first phase must be Demining and Risk Assessment. This clears the immediate physical threat (ERW) and allows the demarcation of chemically hot spots that remain [18].

i. Phytoremediation as a Post Clearance Tool: Once humanitarian demining has secured access, phytoremediation emerges as the most effective and eco-friendly strategy for addressing the diffuse chemical threat. Conventional methods (e.g., incineration, excavation) are costly, energy intensive, and impractical for the large, often remote landmasses contaminated by conflict [14]. Phytoremediation, by contrast, utilizes plants like Vetiver grass or Eurasian water milfoil, which can absorb and transform toxic compounds such as TNT and RDX into nontoxic or less mobile forms in situ [19,20].
ii. Restoring Ecosystem Function: Beyond detoxification, the chosen plant species (e.g., specific grasses or hyperaccumulators) inherently perform two vital ecological functions: stabilization (preventing erosion) and re-establishing microbial communities. This process repairs the "microbial disbalance" caused by explosive residuals, which is crucial for nutrient cycling and long-term soil health [21].
iii. Securing Livelihoods: Selecting robust, economically viable native plant species for phytoremediation (e.g., suitable biomass crops) directly links the remediation process to the restoration of livelihoods. This approach provides a safe, productive use for the land during the detoxification period, thus addressing the community's immediate need for food security and income alongside long-term environmental recovery [10]. The phased model ensures that safety (demining) enables sustainability (phytoremediation), which collectively restores both livelihoods and ecosystem function.

The 4 arguments will be introduced in this paper aimed at innovating in the management of post-conflict land demining and restoration. This paper presents a Policy and Synthetic Perspective Analysis. It is not a systematic review but rather a critical synthesis aimed at bridging disciplinary gaps between Humanitarian Mine Action (HMA), ecological restoration science, and international policy frameworks.

Risk Assessment and Demining as the Precursor to Ecology

The relationship between demining efforts and long-term ecological restoration is a complex nexus where humanitarian urgency meets environmental risk. Risk assessment in post-conflict zones must move beyond simply human safety to encompass chemical contamination and habitat management, viewing demining not as an end but as a precursor to successful ecological stability. The three key questions surrounding this transition highlight the critical need for an integrated, multidisciplinary approach.

Mapping the Invisible Threat: Logistical and Financial Barriers Versus Aerial Systems and AI

The foundational step in addressing explosive remnants of war (ERW) including landmines and unexploded ordnance (UXO) is the accurate mapping of contamination zones. This critical initial step defines the scope of the problem and is essential for humanitarian, development, and environmental planning [22]. However, demining is plagued by significant logistical and financial barriers. Logistically, clearance is an extremely slow, dangerous, and time intensive process. For every hour spent laying mines, up to 100 hours may be required to locate and remove them [23].

Much of the contamination lies in challenging terrain such as dense forests, mountainous areas, or muddy paddies. Clearance teams must often remove extensive vegetation to allow for safe detection, an action that itself can cause secondary environmental damage [24]. Furthermore, natural processes like flooding and gravitational mass movement can cause ERW to migrate, rendering initial maps inaccurate and demanding constant, costly resurveying [25]. Financially, humanitarian mine action is a substantial burden on affected states, most of which are developing countries [23]. While international donor contributions exist, the overall cost to clear and verify land for productive use is immense.

The financial pressure often prioritizes clearing high value land or transportation routes, leaving remote or ecologically sensitive areas contaminated for longer, thereby delaying complete economic and environmental recovery. The presence of landmines and Unexploded Ordnance (UXO) constitutes a profound global humanitarian and developmental crisis, contaminating land in over 78 nations and resulting in thousands of annual casualties [26]. Traditional demining relies heavily on human labour, which is exceptionally hazardous and resource intensive, with estimates suggesting the cost of clearing a single mine can exceed 50 times its original price [26]. Recent technological advancements in remote sensing, robotics, and sensor fusion are rapidly transforming the field, significantly increasing the probability of detection (P_D) while simultaneously reducing the False Alarm Rate (FAR) and human risk.

The most significant recent advancements have focused on wide area reconnaissance and initial threat mapping, primarily using AI enhanced imagery on Unmanned Aerial Systems (UAS), commonly known as drones. UAS platforms offer rapid survey capabilities over inaccessible or large, complex terrains, providing a crucial first layer of data [27]. These aerial platforms are equipped with diverse sensor payloads and advanced Artificial Intelligence (AI) for data processing.

Airborne AI enhanced image processing

Recent advances in AI-enhanced image and signal processing have significantly improved UAV-based landmine detection. Convolutional neural networks (CNNs) and data-fusion algorithms now enable automated recognition of mine-like patterns across GPR, thermal, and hyperspectral datasets [28,29]. These methods enhance feature extraction and target discrimination, reducing false alarms and improving detection reliability in complex terrains. However, challenges remain, including limited radar penetration, air–ground coupling effects, UAV payload constraints, and the high computational demand of real-time inference [30,31].

Airborne Magnetometry and Metal Detection: Drones equipped with high sensitivity magnetometers can detect magnetic anomalies caused by metallic UXOs in the local terrestrial magnetic field, generating heatmaps for visual representation [32]. Furthermore, airborne Electromagnetic Induction (EMI) systems, mounted on drones, have demonstrated high sensitivity, often covering large areas in minutes compared to hours of manual labour, even detecting mines with low metallic content [33].

Airborne ground-penetrating radar (GPR)

Wideband or impulse GPR sensors at low altitude, operators can map shallow subsurface anomalies while remaining at a safe distance [30]. Modern systems employ motion compensation and synthetic-aperture processing to achieve centimetre-scale resolution needed to detect small, low-metal mines [31,34]. Detection accuracy depends on antenna design, soil properties, and flight parameters, and is often improved through sensor fusion—combining GPR with magnetometers, hyperspectral or thermal imaging, and machine-learning-based classification [29,34]. While recent field trials confirm the feasibility of UAV-based GPR, key limitations such as shallow penetration depth, air-layer clutter, and payload constraints remain major research challenges [30,31].

Optical and multispectral imaging

For surface laid or scatter able mines (e.g., PFM1 or “butterfly” mines), high-resolution visible spectrum (VIS) and Near Infrared (NIR) cameras are deployed. Deep learning models, such as YOLOv8, process these optical images in real-time, achieving high accuracy in detection and localization [35]. This approach is often combined with thermal imaging to detect subtle temperature anomalies caused by buried mines influencing the surrounding soil [35].

Sensor fusion and swarms

The concept of Unmanned Aerial Vehicle (UAV) swarms, utilizing multiple drones with varying sensor types (e.g., software defined radar and optical sensors), is being tested for comprehensive, real-time area mapping. Data from these disparate sensors are stitched together at the edge, leveraging cloud-based AI to create detailed operational mosaics and minimize human intervention [36]. A persistent challenge in demining is the high false alarm rate caused by metallic clutter (shrapnel, farming debris) triggering traditional metal detectors. Recent innovations focus on combining sensor modalities and introducing fundamentally new detection physics to address this issue.

A persistent challenge in demining is the high false alarm rate caused by metallic clutter (shrapnel, farming debris) triggering traditional metal detectors. Recent innovations focus on combining sensor modalities and introducing fundamentally new detection physics to address this issue.

a. Dual Modality Sensor Fusion: The most mature technological solution for improving discrimination is the fusion of Ground Penetrating Radar (GPR) with Metal Detectors (MD) or EMI. GPR emits electromagnetic waves into the ground to image subsurface objects, distinguishing between non-metal mines and metallic clutter, while MD identifies metal objects [37]. By fusing data at the feature or decision level, integrated handheld systems have been proven in field trials to decrease false alarm rates by 77% to 96.5% compared to single sensor use [38].
b. Nuclear Magnetic Resonance (NMR) Detection: A ground breaking innovation involves handheld detectors based on Nuclear Magnetic Resonance (NMR), which is designed to respond directly to the chemical signature of the explosive material (e.g., sodium, potassium, and chlorine atoms) rather than the casing or metal content [39]. In field trials, NMR technology was found to virtually eliminate false positives caused by metallic debris, allowing deminers to doublecheck high-risk locations with precision before excavation [39].
c. Contamination Profile: Explosive Derived Chemical Risks: Beyond the physical danger, the chemical contamination from conventional explosives introduces Toxic Remnants of War (TRW) into soil and water systems. The most found contaminants are TNT (2,4,6trinitrotoluene) and RDX (Hexahydro1,3,5trinitro1,3,5triazine) [40,41].

These compounds are potent nitroaromatics that pose long-term ecological risks. TNT tends to soil particles, limiting migration, but RDX has a low soil sorption coefficient and readily leaches into groundwater, presenting a significant risk to drinking water supplies [42,43]. Both TNT and RDX are classified as possible human carcinogens and can damage the nervous system, liver, and blood [42]. The degradation of these parent compounds in the environment often produces by-products, such as amino Dinitro toluene (DNT), which can be even more toxic than the original material [40,41]. Additionally, the explosive casings, detonators, and fuses introduce heavy metals, including lead, mercury, and arsenic, into the environment [44]. These nonbiodegradable substances accumulate in the soil and sediments, bioaccumulate in the food chain, and require highly specialized remediation strategies, confirming that demining is as much a hazardous waste clean-up operation as it is a safety measure.

Demining as Habitat: The Minefield Paradox

The concept of the “Averting the Tragedy of the Minefield” phenomenon is a valid paradox demonstrating that landmines can inadvertently act as biodiversity conservation tools. By making large tracts of land inaccessible and deadly to humans, minefields create involuntary exclusion zones (Climate Diplomacy, 2022). This absence of human activity, such as logging, agriculture, poaching, and settlement, allows ecosystems to recover. A prominent case is the Korean Demilitarized Zone (DMZ), which, despite being heavily mined, has become a recognized ecological sanctuary where endangered species thrive (Climate Diplomacy, 2022). This environmental benefit, however, is temporary and comes at a humanitarian cost. The challenge lies in the need to manage demining to minimize secondary habitat destruction. Traditional clearance techniques that involve indiscriminate burning or bulldozing of vegetation to gain access directly destroy the very habitats that the mines preserved [24]. Therefore, demining operations must adopt environmentally sensitive practices.

This includes using methods that reduce vegetation clearance to the bare minimum, employing bio detection methods, and integrating environmental assessments into the clearance plan. Crucially, post clearance planning must include sustainable land use strategies to prevent the immediate reintroduction of destructive human activities and ensure the long-term conservation of the biodiversity the minefield temporarily protected [24]. The necessity of demining as a precursor to sustainable ecology is undeniable. Successful ecological restoration hinges on the ability to overcome the logistical and financial barriers to clearance, manage the long-term chemical contamination threats, and carefully navigate the paradox of preserving ecosystems as human access is restored.

Humanitarian Mine Action (HMA) is a vital global effort focused on protecting human lives and restoring livelihoods by clearing landmines and other explosive remnants of war (ERW). However, while the primary objective is inherently humanitarian, the operational methods employed in demining activities themselves pose a significant, often overlooked, threat to the environment, leading to secondary habitat destruction [45]. Effective management of demining is not merely an optional best practice but an ethical and ecological imperative to ensure that the process of making land safe does not inadvertently make ecosystems unstable. The primary ecological damage resulting from ERW contamination is the exclusion of human populations from resource rich areas, often leading to overexploitation and soil degradation in accessible, uncontaminated zones [46]. Ironically, contamination can sometimes create protective havens by preventing human entry, allowing biodiversity to flourish in the minefield itself. The paradox arises when the clearance process designed to remedy the original threat destroys these protected habitats through aggressive clearance techniques [47].

The most potent source of secondary damage is the indiscriminate use of mechanical clearance equipment, such as flails and tillers. While efficient for rapidly processing vast areas, these heavy machines inflict severe and sometimes irreversible soil compaction and structure loss [48]. Soil is a finite, living resource, and this damage undermines long-term agricultural viability, water retention, and microscopic underground habitats essential for ecological recovery. Furthermore, the operational requirements of demining often involve extensive vegetation removal to create access routes or to ensure line of sight for manual and technical survey teams. This clearance, particularly in biodiverse shrubland and forest, acts as a catalyst for land transformation. Following clearance, communities, driven by livelihood pressures, rapidly convert the stripped land into agricultural fields, leading to deforestation, accelerated erosion, and a noticeable decline in local biodiversity, including medicinal plants and wild food sources [49].

The Mandate for Environmental Management

The necessity of rigorous management is recognized under the "do no harm" principle, which requires mine action organizations to consider the potential negative impacts of clearance [45]. This has led to the integration of environmental safeguards throughout the International Mine Action Standards (IMAS), particularly IMAS 07.13, which mandates the consideration of environmental and climate risks [50]. Effective management relies on three key strategies.

Prioritizing land Release (LR) principle

The single most effective way to minimize the environmental footprint is by reducing the actual area subject to physical clearance [50]. By maximizing the use of nontechnical survey (NTS) and technical survey (TS) methods collectively known as Land Release organizations can accurately confirm or cancel suspected hazardous areas, limiting the deployment of destructive mechanical assets to only the land where contamination is virtually certain. This avoids clearing uncontaminated land simply because it was previously marked as suspicious.

Integrating Environmental Impact Assessment (EIA)

Before operations commence, Mine Action programs must conduct comprehensive ecological sensitivity assessments [50]. This planning step identifies ecologically critical zones, such as sensitive wetlands, rare plant habitats, or critical wildlife corridors. Knowing this baseline information allows managers to adapt their approach by:

i. **Minimizing Vegetation Clearance:** Preserving vegetation cover, especially in steep or biodiverse areas [50].
ii. **Adapting Methodology:** Switching from mechanical clearance to manual or animal assisted detection (e.g., mine detection dogs) in sensitive habitats where soil integrity is paramount (JMU Scholarly Commons, n.d.).
iii. **Controlling Pollution:** Implementing protocols for the regular and safe disposal of operational waste, including hazardous oils, fuels, and human waste, to protect local water supplies and soil (JMU Scholarly Commons, n.d.).

Addressing Post Clearance Land Use

Environmental management cannot end when the mine is removed. A significant part of the necessary management involves collaborating with local communities on sustainable land management strategies [50]. Without this, the rapid shift to unsustainable agricultural practices following clearance causes the secondary destruction cycle to continue. Post clearance efforts should include supporting soil restoration, manage the spread of invasive species, and promote climate resilient farming techniques to ensure that the safe land remains productive and ecologically stable for the long term. To summarize, managing demining activities to minimize secondary habitat destruction is a core component of responsible humanitarian action. The risk of unintentionally undermining long-term ecological stability through mechanical disturbance, vegetation stripping, and poor waste management is significant. By rigorously applying Land Release principles, conducting mandatory environmental assessments, and implementing ecologically sensitive clearance techniques, mine action organizations can fulfil their humanitarian mission while upholding the ethical imperative to "do no harm" to the environments they seek to restore.

Ecological Detoxification and Soil Healing

The clearance of landmines and unexploded ordnance (UXO) is a critical first step in restoring human safety, but it often precedes a much more complex challenge: ecological recovery. Habitats affected by conflict face a triple threat: chemical contamination from explosive residues, physical degradation from military activity and mechanical clearance, and biological collapse due to the loss of soil organic matter (SOM) and microbial diversity (Mine Action Review, 2021). Effective habitat restoration requires an integrated, nature-based approach that addresses both chemical pollutants and structural soil damage. Explosive remnants of war (ERW) release toxic energetic compounds into the soil and groundwater, including trinitrotoluene (TNT), hexahydro1,3,5trinitro1,3,3,5 triazine (RDX), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX). These compounds pose a long-term threat due to their toxicity and potential to leach into water sources (GICHD, 2021). The state-of-the-art in treating these residues favours cost effective, passive techniques, with phytoremediation being a leading biological solution.

State of the Art Explosive Treatment

While methods like incineration and solvent extraction are fast, they are expensive, generate secondary waste, and destroy soil structure [51]. Phytoremediation, conversely, uses plants and their associated microorganisms to degrade or stabilize contaminants in place. Phytoremediation works through several processes:

a. Phytodegradation: Plants, particularly grasses like switchgrass (Panicum virgatum) and various members of the Poaceae family, are effective at degrading explosives. The enzymes released by the plant roots, often in collaboration with rhizosphere bacteria, metabolize TNT and RDX into nontoxic or less mobile compounds [52].
b. Phytoextraction: Certain plants, including hyperaccumulators like specific species of mustard (Brassica sp.), can absorb heavy metals (such as lead, mercury, or cadmium) released from munitions casings and transport them to their shoots for eventual harvest and safe disposal.
c. Phyto-stabilization: Plants reduce the mobility of contaminants by limiting wind and water erosion, stabilizing the soil, and decreasing the leaching of pollutants into groundwater.

Challenges in Applying Phytoremediation in Conflict Soils

Despite its promise, applying phytoremediation in post-conflict zones faces unique difficulties driven by the extensive damage to the environment [53].

Table 1: Challenges in Applying Phytoremediation in Conflict Soils.

Challenge	Impact on Phytoremediation Success
Physical Disturbance/ Compaction	Heavy mechanical clearance equipment (flails, tillers) causes severe soil compaction, restricting root penetration and limiting gas and water exchange, which hinders plant establishment (Mine Action Review, 2021).
Nutrient Poverty	Extensive vegetation clearing removes organic matter, leading to poor nutrients, inert soil. This low fertility compromises the growth and biomass of the remediation plants, which need energy to produce detoxifying enzymes (Van Aken & Braland, 2017).
Chemical Stress	Acidification or alkalinisation caused by detonation residues and the presence of high concentrations of heavy metals can be toxic to many remediation species. The altered pH may also make contaminants more bioavailable or immobile, depending on the compound.
Erosion	The loss of topsoil and vegetative cover exposes the remediation area to wind and water erosion, physically washing away young plants and spreading contaminants to uncontaminated areas (Impact Initiatives, 2025).

Restoring Soil Structure and Function

For phytoremediation to be successful, the soil must first be physically and biologically capable of supporting plant life. Therefore, addressing structural damage and stimulating biological recovery is crucial. This is achieved through the strategic application of biological and organic soil amendments. The goal is to rapidly reintroduce soil organic matter (SOM) and the beneficial microbial communities essential for nutrient cycling and contaminant degradation.

i. Compost and Biosolids: Applying compost (derived from agricultural or yard waste) or treated biosolids is highly effective for jumpstarting recovery. These amendments immediately boost SOM, providing essential nutrients (nitrogen, phosphorus) and dramatically improving water holding capacity and aeration. Crucially, compost reintroduces a diverse population of native microorganisms, many of which are specifically adept at breaking down explosive compounds [48].

ii. Biochar: This charcoal-like substance, produced by heating biomass in a low oxygen environment, offers several benefits. Biochar acts as a stable carbon sink, which enhances SOM, but its primary function in remediation is its high surface area and porosity. This structure helps to rapidly adsorb and immobilize certain heavy metals and some organic pollutants, stabilizing them while allowing plant roots to establish [54].

iii. Mycorrhizal Fungi Inoculation: Mycorrhizal fungi form symbiotic relationships with plant roots, extending the root system's effective reach for water and nutrients. In nutrient poor, sterile conflict soils, inoculation with these fungi is vital. They enhance the stress tolerance of remediation plants and, through their extensive hyphal networks, help rebuild soil aggregation and structure lost due to physical disturbance [48].

These bio amendments collectively address the physical, chemical, and biological deficiencies of conflict soils, creating a hospitable environment for long-term ecological succession.

Water Remediation and Nature Based Solutions

Physical and chemical damage from conflict is often exported to local and regional water bodies through surface runoff. Toxic runoff carries heavy metals, undegraded explosive compounds, and sediment, impacting downstream ecosystems and human water sources. Nature based solutions (NBS) are recommended for filtering these pollutants passively and sustainably.

Constructed Wetlands: These engineered systems mimic natural wetlands and are highly effective for filtering wastewater and stormwater runoff. Wetlands contain specific soil media, plants (such as reeds and rushes), and microbial layers that perform a cascade of pollutant removal:

a. Sedimentation: Slow water flow allows sediment and particulate bound contaminants to settle out.

b. Phytoremediation/Rhizofiltration: Wetland plants absorb dissolved contaminants (including heavy metals and trace explosives) through their roots.

c. Microbial Degradation: The anaerobic and aerobic zones within the wetland sediment create ideal conditions for specialized bacteria to break down complex organic pollutants [54].

d. Vegetated Filter Strips and Buffer Zones: Establishing dense strips of native perennial grasses or trees along stream banks and drainage channels is a simple yet powerful NBS. These buffer zones intercept surface runoff, slowing the water and promoting infiltration, which allows contaminants to be adsorbed by the soil and degraded by rootzone microbes before reaching the main water body.

In conclusion, the ecological restoration of conflict affected land demands a planned sequence of intervention. By integrating site specific phytoremediation techniques with robust soil amendments (compost, biochar, and fungi) and employing downstream nature-based water filtration, the legacy of explosive contamination can be successfully addressed, leading to sustainable habitat recovery and the return of safe, productive land.

Sustainable Land Reuse and Socio-Economic Resilience

This analysis addresses the post-demining phase of recovery, focusing on the ethical and practical necessity of rapidly transitioning land back into productive use to secure community livelihoods and promote long-term peace. The approach integrates humanitarian, environmental, and socio-political considerations. The removal of explosive remnants of war (ERW) marks a crucial transition from security intervention to sustainable development. The goal of humanitarian mine action has shifted beyond mere physical clearance to encompass the rapid and responsible use of returned land [55]. This integrated approach recognizes that the environmental and economic health of a community is inextricably linked to its long-term stability and resilience (UNDP, n.d.).

Prioritizing Livelihoods and Food Security

The imperative to prioritize land uses that restore livelihoods and food security immediately following demining is both an ethical duty and a practical necessity. Ethically, populations, particularly those displaced, often return to devastated areas with immediate needs for food and income. Rapidly returning agricultural land to production directly addresses Sustainable Development Goal (SDG) 2: Zero Hunger, and SDG 8: Decent Work and Economic Growth [57]. Practically, the presence of ERW often forces communities onto fragile, accessible land, leading to unsustainable practices like overharvesting or logging, which causes further environmental degradation [58].

By prioritizing the clearance and immediate transition of high value agricultural land, mine action can stabilize rural economies, reduce reliance on humanitarian aid, and prevent environmental pressures on remaining safe areas [55]. Furthermore, employment opportunities within the clearance and subsequent restoration projects themselves, often recruiting ex-combatants can contribute significantly to the reconciliation and social reintegration process [59]. To ensure that post-conflict land restoration builds lasting community resilience, we propose a tiered engagement framework centered on livelihood integration. This approach moves beyond simple aid by creating sustainable, skill-based economic opportunities directly linked to the safety clearance and restoration processes. Four key models for livelihood engagement are suggested:

i. Direct Employment in Safety & Restoration (Technical Capacity Building): Training and employing local community members as field technicians for advanced tasks, such as the deployment and maintenance of proposed biosensors for explosive residue detection or utilizing GIS and drone mapping for risk assessment and land survey. This builds high-value, transferable skills within the affected population.

ii. Sustainable Land Use (Ecological Revitalization): Implementing agroforestry and permaculture systems on newly cleared land. By prioritizing low-impact, multi-layered farming over conventional monoculture, communities can rapidly rebuild soil health and secure long-term, diverse food and resource streams, directly supporting household income and nutritional security.
iii. Economic Diversification (Value-Added Assets): Establishing community-led eco-tourism or war-heritage tourism initiatives. These ventures are linked to the protection and appreciation of restored ecological sites (e.g., protected wetlands or reforested areas), providing a stable, non-extractive income source that incentivizes long-term environmental stewardship.
iv. Resource Management (Governance and Ownership): Implementing co-management bodies. This formal structure ensures local leaders and traditional land custodians are empowered to guide critical long-term decisions, including species selection (native vs. non-native) and overall land management protocols, ensuring the restoration aligns with local needs and cultural practices.

Sustainable Agriculture and Agroforestry Systems

For demined land, the restoration of productive use should align with low impact, sustainable farming practices to avoid exacerbating soil damage from previous conflict and clearance operations [60]. Transitioning to sustainable agriculture or agroforestry systems offers a crucial balance between productivity and ecological health:

a. Minimizing Soil Disturbance: Instead of returning to industrial, high tillage farming that can further degrade fragile, post-conflict soils, a focus on no-till or conservation agriculture minimizes erosion and protects the developing microbial communities essential for soil recovery.
b. Agroforestry Benefits: Integrating trees and shrubs with crops (agroforestry) provides multiple benefits, including soil stabilization, natural fertilization (e.g., nitrogen fixing species), and increased crop resilience to climate variability. The tree component also offers diversified income sources, reducing dependence on a single annual crop.
c. Native Inputs: Relying on native inputs such as locally sourced organic compost and local crop varieties, rather than imported chemical fertilizers and pesticides, ensures that the farming system is appropriate for the local ecosystem and minimizes the risk of introducing new environmental contaminants. This approach not only aids environmental recovery but also enhances the resilience and food sovereignty of the community [57].

Infrastructure Reuse (Green Solutions)

Military conflict inevitably leaves behind vast amounts of "violent infrastructure" concrete bunkers, hardened emplacements, trenches, and metal barriers. Instead of costly and destructive removal, these remnants can be creatively repurposed into valuable ecological features [61]. This form of Engineering with Nature (EWN) transforms liabilities into assets:

i. Erosion Control and Water Management: Concrete barriers and trench lines can be stabilized and reinforced with vegetation to create check dams or terracing features that slow rainwater runoff, prevent soil erosion, and promote water infiltration. Former trenches can be adapted into swales or drainage channels for localized water management.
ii. Wildlife Habitats: Solid, concrete bunkers or damaged buildings, if structurally safe, can be partially covered with soil and vegetation to become unique, sheltered habitats. The ruins create diverse microclimates shady, moist niches or sunny, heat retaining rock piles which are ideal for specialized flora and fauna, enhancing biodiversity [61].
iii. Recreational and Cultural Features: The adaptive reuse of military relics can be integrated into landscape planning as historical markers, viewing points, or features within nature parks, transforming sites of trauma into spaces for memory, recreation, and education, thereby promoting reconciliation and community healing [62].

Conflict Sensitive Landscape Planning

For land use decisions to be successful and contribute to peace, they must be executed through conflict sensitive landscape planning that is fundamentally participatory. Land is often a disputed resource in post-conflict settings and returning it without a consensual plan can ignite new tensions [58]. A participatory process requires the following:

a. Involving Displaced and Affected Populations: Consultations must involve all relevant stakeholders, including internally displaced people (IDPs) and marginalized groups. This ensures that the priorities for land clearance and reuse (e.g., access to water points, critical grazing land, or sacred sites) reflect their immediate needs and traditional knowledge, rather than being dictated by external or state actors.
b. Utilizing Local Ecological Knowledge (LEK): Local communities possess deep knowledge of soil types, microclimates, and traditional farming techniques. Integrating this LEK into planning for instance, deciding where to plant native agroforestry species or how to manage water flows results in more sustainable and culturally resonant outcomes [59].
c. Peacebuilding Through Environmental Cooperation: Cooperative environmental planning inherently forces formerly opposed groups to collaborate on a shared, non-political goal: the health of their common landscape. This cooperation builds trust, establishes common ground, and reinforces the social contract in fragile post-conflict environments [63].

Ultimately, prioritizing productive use, implementing sustainable farming practices, creatively repurposing infrastructure, and employing a conflict sensitive planning process transforms mine action from a purely technical task into a powerful engine for peacebuilding and sustainable community development.

Conclusion and Policy Implications

Achieving sustainable peace requires simultaneously tackling humanitarian safety and environmental remediation. This paper argues that the success of post-conflict ecological recovery is directly constrained by how quickly and effectively human security can be established. The analysis concludes by urging international policymakers to fully integrate these interconnected objectives through targeted financing and concrete policy shifts.

Synthesis

The Safety Ecology Constraint: The core finding is that post-conflict ecological recovery is a slow process where the speed of ecological recovery is fundamentally limited by the speed and effectiveness of humanitarian safety and risk management. Conflict causes severe, pervasive damage not only to infrastructure but also to natural resources which directly translate into acute humanitarian crises [64,65]. This constraint is evident across several dimensions:

a. Unexploded Ordnance (UXO) and Contamination: The presence of landmines and explosive residues (e.g., trinitrotoluene or TNT) renders vast swathes of land unusable for agriculture, forestry, or conservation. Ecological restoration cannot commence until these areas are cleared, a process entirely dependent on military and humanitarian demining operations [66] safety is the prerequisite for access.
b. Public Health and Environmental Hotspots: The collapse of public health systems and the destruction of vital infrastructure, such as water and sanitation facilities, create conditions where infectious diseases emerge and transmit rapidly [67]. Furthermore, industrial and military targets often become environmental hot spots (contaminated sites) that pose severe risks to human health (United Nations Environment Programme [68]. Until these immediate human health risks are remediated, often through environmental clean-up, the focus cannot shift to long-term biodiversity or ecosystem restoration [69].
c. Displacement and Resource Strain: Mass population displacement into temporary settlements puts extreme pressure on remaining ecological resources (e.g., forests for fuel, water sources), further compounding environmental degradation [67]. Humanitarian stability (ensuring safe returns or provision of sustainable settlement resources) is therefore essential to halt secondary environmental damage before primary recovery can proceed. In essence, environmental protection and civilian protection are inseparable in this context; managing war-related environmental damage is inherently a humanitarian imperative [69].

Future Research: Prioritizing Field Ready Solutions

To overcome the security ecology constraint targeted technological and methodological advancements are urgently needed:

Developing rapid, field deployable biosensors for detecting explosive residues

Conventional methods for detecting explosive residues (e.g., Gas Chromatography Mass Spectrometry or GCMS) are precise but are expensive, bulky, and require laboratory conditions, making them unsuitable for largescale, continuous field monitoring in remote or dangerous post-conflict zones [66,70]. Critical research needs to focus on portable biosensors that mimic highly sensitive biological detection systems. Advances in synthetic biology and microbial engineering have shown promise in developing microbial systems (e.g., using Pseudomonas putida or E. coli) that react to chemical signals like 2,4dinitrotoluene (2,4DNT) and emit a measurable or visible result [70,71]. Further research should focus on:

a. Robustness and Shelf Life: Enhancing the stability and longevity of these biosensing systems for use in harsh environmental conditions.
b. Multitarget Detection: Creating sensors capable of simultaneously identifying a broader spectrum of explosives, including TNT, RDX, and heavy metals.
c. Integration: Pairing biosensors results with portable analytical techniques like Surface Enhanced Raman Spectroscopy (SERS) for forensic level validation in the field [66].

Creating standardized ecological assessment protocols for conflict zones

Effective remediation and restoration require a rapid, consistent, and replicable method for prioritizing sites. Current approaches are often ad hoc or rely on traditional methodologies not designed for the unique challenges of insecure, contaminated areas. Future research must establish standardized, rapid ecological assessment protocols that:

a. Prioritize Risk: Systematically apply the source pathway receptor approach to rank contaminated and mined sites based on the greatest risk to human health and critical ecosystem services [13].
b. Integrate Remote Sensing: Standardize the use of satellite imagery, drone mapping, and Geographic Information Systems (GIS) to assess damage extent and baseline conditions where access is limited on the ground.
c. Establish Baseline Metrics: Define a core set of ecological integrity metrics (e.g., soil health, water quality, biodiversity indicators) that can be measured and consistently tracked by local and international teams to monitor recovery against predefined restoration standards [72].

Policy Call: linking security and humanitarian funding to environmental peacebuilding

A fundamental shift in international funding mechanisms is required to ensure sustainable post-conflict peace. The analysis concludes by urging international bodies to link security and humanitarian funding directly to ecological restoration and sustainable land management initiatives, treating environmental peacebuilding as a key component of post-conflict reconstruction. Currently, financing for security (e.g., demining, stabilization) and humanitarian response are often siloed from long-term development and environmental protection [69]. This separation is inefficient and risks undermining stabilization efforts, as resource scarcity and environmental degradation are often root causes or multipliers of conflict [73]. Specific policy actions should include:

a. Integrated Funding Streams: Mandating that a fixed percentage of all post-conflict security and humanitarian aid budgets be earmarked for the remediation of environmental hot spots and restoration of critical livelihood resources (e.g., water sources, agricultural land, [69].
b. Conditionality: Tying funds for reconstruction and security sector reform to verifiable benchmarks in land clearance (UXO and contamination) and the implementation of sustainable natural resource governance structures.
c. Empowering Local Actors: Investing in the capacity of local and national institutions to manage environmental assets and lead restoration projects, thereby creating emergency employment, restoring livelihoods, and ensuring the long-term sustainability of peace [69]. By prioritizing environmental peacebuilding, the international community can foster resilient, self-sustaining systems that minimize the risk of relapsing into conflict [72-89].

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