INNOVATION HUB

BROUGHT TOGETHER BY THE GICHD

LAND RELEASE RESEARCH AGENDA

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ABBREVIATIONS

ADS	animal detection system
AI	artificial intelligence
APM	antipersonnel mine
AVM	antivehicle mine
CHA	confirmed hazardous areas
EMI	electromagnetic induction
EO	explosive ordnance
GIS	geographic information system
GPR	ground-penetrating radars
IED	improvized explosive device
IMS	ion mobility spectrometry
LiDAR	light detection and ranging
MR	magnetic resonance
NMAA	national mine action authority
NQR	nuclear quadrupole resonance
NTS	non-technical survey
RDX	research department explosive
RFI	radiofrequency interference
RGB	red, green, and blue
SHA	suspected hazardous areas
SNR	signal-to-noise ratio
TNA	thermal neutron analysis
TNT	trinitrotoluene
TS	technical survey
UAV	uncrewed aerial vehicle
UGV	uncrewed ground vehicle

Land Release Research Agenda, Geneva International Centre for Humanitarian Demining (GICHD), June 2026 © GICHD

Cover: A warning sign marks the entrance to a safe lane in a minefield. Ratanak Mondol district, Battambang province, Cambodia.

CONTENTS

INTRODUCTION

Research agendas, developed under the Mine Action Innovation Hub, serve as practical guides that outline key research needs and provide stakeholders with an evidence-based foundation for setting research priorities.

This edition of the research agenda focuses on the challenges affecting the efficiency, effectiveness, and safety of land release, as well as the technologies or methods currently used to address them, including their limitations.

The agenda was developed using a qualitative and consultative approach based on two inputs:

- stakeholder consultations through the Innovation Hub with sector representatives; and
- a literature review to identify key challenges, capability gaps, and current technologies grounded in field realities.

The research agenda reflects operational constraints at one moment in time, so its priorities may change as new challenges arise. Although the consultation process was wide, it may not reflect all the points of view of affected countries or stakeholders. In addition, the literature review focused on English-language sources, which may limit regional insights.

The land release research agenda is a first step to prioritize research and innovation needs in the mine action sector. As such, it offers a blueprint for the development of other sector-specific research agendas tailored for specific thematic or geographical contexts.

1. BACKGROUND: THE CONCEPT OF LAND RELEASE

In mine action, land release is an evidence-based process of applying all reasonable effort to identify, define, and remove all presence or suspicion of explosive ordnance (EO) through non-technical survey (NTS), technical survey (TS), and/or clearance.[1] As part of the process, national mine action authorities (NMAAs) define what all reasonable effort means in their own context.[2]

NTS gathers and analyses information about the presence and nature of EO contamination. It uses non-intrusive methods, without entering the hazardous areas or handling EO directly. On the other hand, TS uses intrusive interventions to actively investigate the ground or structures–using tools that disturb or examine the subsurface–to confirm where contamination is present or not. Intrusive methods may include detectors, machines, animal detection systems (ADS), and/or remote-sensing methodologies.

Both NTS and TS support land release decisions, including the classification of areas as suspected (SHA) or confirmed (CHA), based on direct or indirect evidence. During survey, the location of every item of EO is not needed, if the information gathered is enough to determine the boundaries of hazardous areas, which can then be cancelled, reduced, or cleared. However, reliable evidence and data are essential for understanding contamination and allocating resources effectively. Clearance entails systematic detection, removal, and/or disposal of EO, according to the established clearance criteria.[3]

Land release operations take place in increasingly complex environments, including in urban areas or challenging terrain, with varying types and mixed EO contamination, the growing use of improvised explosive devices (IEDs), and in contexts where funding is limited. In these conditions, more reliable information becomes increasingly important, as do improved standards and innovative tools that can strengthen operational efficiency, effectiveness and safety.

A range of emerging methods and technologies offer opportunities to address these challenges. Remote-sensing, stand-off robotics, sensor fusion and artificial intelligence (AI)-powered technology can significantly enhance EO survey, detection, and disposal, while reducing risks to personnel and impacted people. New learning and training platforms ease accessibility and foster cross-learning and knowledge-sharing.

However, no single methodology or technology can address all types of EO contamination and operational contexts. For example, different approaches are required to conduct the land release process in the suspected presence of anti-personnel mines (APM), low-metal content mines, cluster munition or unexploded artillery shells and aircraft bombs. A deminer's toolbox approach remains essential.

2. GLOBAL CHALLENGES

The following analysis presents some of the systematic challenges facing land release, based on the findings from stakeholder consultations and a comprehensive literature review. The analysis focuses on four core operational challenges that constrain land release today. These are:

DETECTION

The efficient detection of EO.

LOCATION

The precise location and delineation of contaminated areas.

EXCAVATION

The safe and efficient excavation of buried threats.

DISPOSAL

The safe disposal of EO.

Each challenge is presented through a problem statement outlining its impact on land release processes, followed by a brief analytical description that explains the nature of the challenge and its underlying drivers. For each challenge, a set of research questions is included to guide further research and analysis.

DETECTION

Limitations in explosive ordnance detection–including accuracy, signal discrimination, depth penetration, and performance variability across environmental conditions constrain the effectiveness and efficiency of technical survey and clearance.

The problem statement above combines four factors limiting the detection of EO.

- **Accuracy:** The ability of a detection system to correctly identify the presence of EO without missed items.
- **Signal or clutter discrimination:** The capacity to distinguish EO from other metallic clutter, soil anomalies, or other non-threatening objects, reducing the number of false alarms.
- **Depth penetration:** The maximum depth below the surface at which a detection system can reliably identify buried EO.
- **Performance variability:** The degree to which detection effectiveness changes under different environmental conditions, such as soil type, mineralization, moisture, temperature, vegetation, or terrain.

Hand-held electromagnetic induction (EMI) detectors, commonly referred to as "metal detectors", remain the primary detection tool. They function by detecting metallic content of subsurface objects, which serves as an indirect indicator of potential EO. However, they often fail to distinguish between metal clutter and actual EO,[4] leading to false alarm ratios of up to 100:1.[5] Each detected anomaly often triggers costly and slow manual excavation to verify whether EO is present. Improving signal discrimination is therefore essential to improve efficiency and resource allocation.[6] Other researched and tested sensors commonly rely on detecting other proxy anomalies (such as variations in soil density, magnetic response, or thermal signatures) but each one has specific limitations that impact its overall performance and applicability.[7]

- EMI detectors have limited capability in detecting low-metal EO, including IEDs primarily made of plastic or wood.
- Environmental factors may significantly affect the performance of detection technologies, ranging from handheld EMI to uncrewed aerial vehicle (UAV)-mounted sensors.[8] For example, the accuracy of EMI sensors declines in highly mineralized or ferrous soils, while wet clay conditions may reduce the effectiveness of ground-penetrating radars (GPR). The performance of light detection and ranging (LiDAR) can be degraded by dense fog and heavy rainfall.[9] High soil magnetic susceptibility may obscure weak signals at greater depth, increasing false alarm rates or resulting in missed items.[10]
- EMI detectors often operate at relatively shallow depths, which presents challenges when searching for low-metal content mines, both AP and anti-vehicle mines (AVM). In some cases, nationally prescribed clearance depths exceed the effective detection capability of these systems, creating operational constraints. In addition, environmental conditions and specific types of EO deployment often cause EO to be found deeper, as in the event of flooding or shifting sand.
- Forestry areas and dense vegetation, as well as steep and rocky ground, may restrict access and reduce the suitability and effectiveness of deployed equipment and sensors.[11]

Metal detectors remain the most commonly used detection tool. Norwegian People’s Ain (NPA) deminer using a handheld metal detector in a cluster munition remnants survey (CMRS) task in Ratanakiri, Cambodia. © GICHD 2026

Multi-sensor fusion is often presented as a way to address the limitations of individual technologies. For example, dual-sensor detectors integrating EMI and GPR can reduce false alarm rates down to 40:1 on coarse, dry, low-conductivity soils.[12] However, experience to date indicates that combining multiple sensors also has limitations. In less favourable soil conditions, false alarm ratios may still range from 100 to 1,000 for every landmine detected.[13] In addition, dual-sensor detectors require much greater operator training and units can cost up to ten times more than the standard metal detectors, raising questions about scalability and cost-effectiveness.

Direct detection of explosive substances represents a critical area of research aimed at improving signal discrimination and significantly reducing false positive rates. While Animal Detection Systems (ADS)–such as mine detection dogs and rats–remain the most established form of biological vapor sensing in the sector, emerging research focuses on digitizing and automating these capabilities through two primary chemical analysis techniques.

- **Molecular spectroscopy** detects explosive substances using radiofrequency waves, lasers or neutrons. Techniques such as magnetic resonance (MR),[14] nuclear quadrupole resonance (NQR),[15] or thermal neutron analysis (TNA)[16] fall under this category.

- **Vapor sensing** identifies the chemical signature of explosive substances by detecting microscopic trace particles or gas molecules emitted into the air or soil. This includes gas chromatography,[17] ion mobility spectrometry (IMS),[18] and biosensors that use genetically modified plants or microorganisms capable of reacting to explosive compounds[19].

Despite their potential, significant limitations still prevent the wide field deployment of these technologies. NQR systems are for example constrained by the presence of metallic casings, which can interfere with detection accuracy and are highly susceptible to radiofrequency interference. In addition, current systems have not reached the production maturity for their use in land release, and unit costs remain several times higher than those of metal detectors.

Many of these sensor technologies remain highly susceptible to environmental noise. Neutron-based systems, such as those used in TNA, can penetrate material at significant depths and provide detailed information on material properties and composition. However, the nitrogen signatures associated with explosives can be obscured by signatures from common elements present in both soil and explosives, such as hydrogen or chlorine.[20] Additional barriers to field deployment include equipment size and weight, the need for radiation shielding, and the requirement for advanced data processing and signal analysis capabilities.

Vapor-sensing techniques face different challenges. Most encountered explosives, such as trinitrotoluene (TNT) and research department explosives (RDX) have extremely low vapor pressures, where the substance evaporates very slowly and releases very few molecules. When the explosives are well contained within thicker intact casings, vapor emission is further reduced and can become nearly undetectable.

Until these systems can reliably distinguish trace explosive molecules from environmental interference and be integrated into portable, field-ready designs, they remain technically immature for land release deployment. Further research, engineering refinement, and investment are required to overcome these limitations.

Research questions

To overcome current EO detection limitations, future research could focus on the following key questions:

1. How can detection technologies be enhanced to achieve reliable identification of minimum-metal or non-metal EO at operationally deployable maturity levels and at an affordable cost?

2. How can subsurface detection performance be improved to reliably identify EO (including minimum-metal items) at nationally prescribed clearance depths and beyond, while maintaining operational feasibility, productivity, and affordability?

3. What combinations of hardware, signal processing, and machine learning can reduce false alarm rates without compromising the probability of detection, particularly in mineralized or metal-cluttered environments?

4. What technological advances are required to make explosive compound detection affordable, portable, and reliable for field deployment?

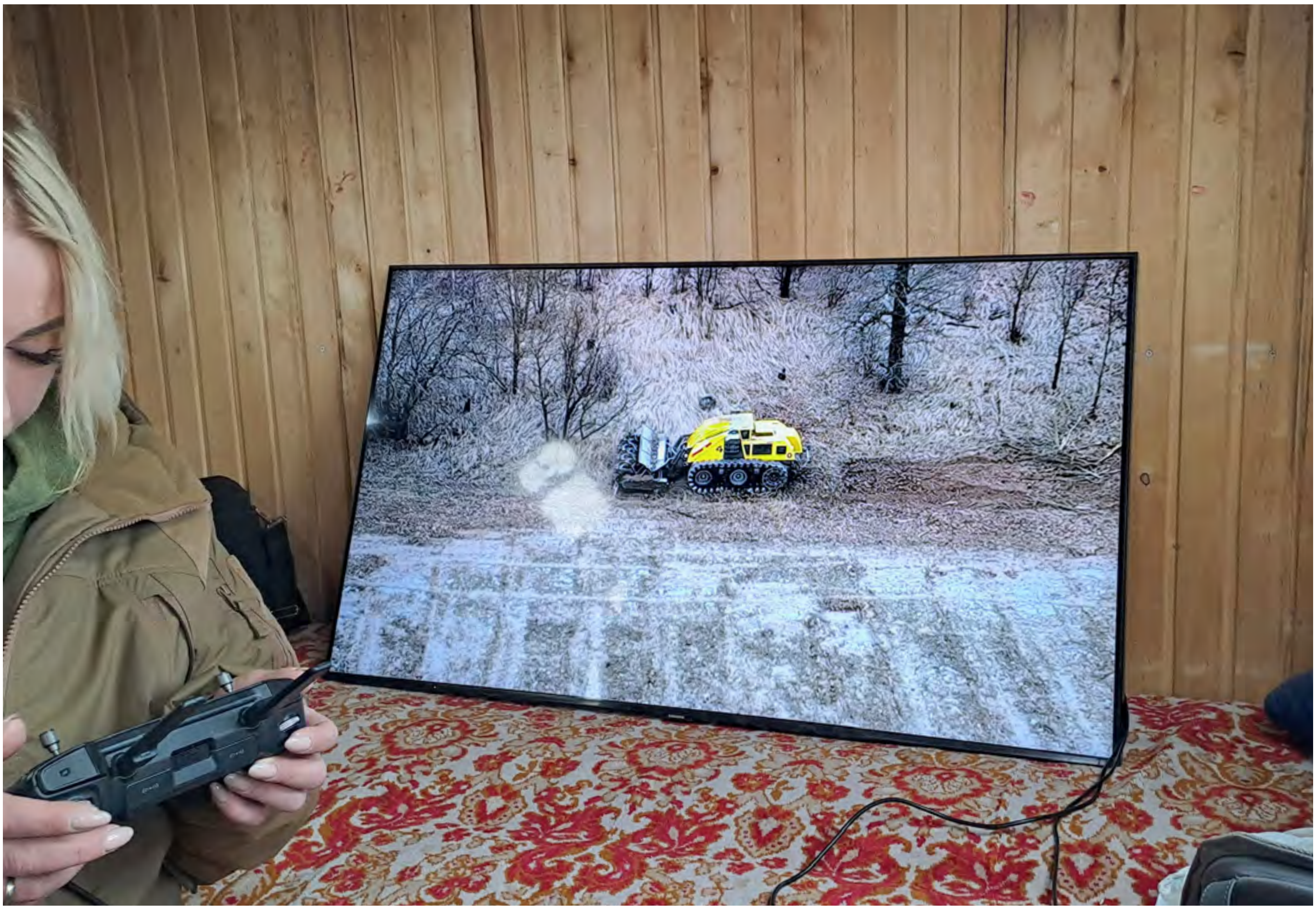
5. How can detection technologies and operational methodologies be optimally matched to specific environmental conditions, contamination types, and hazard profiles, including when knowledge on the contamination and environmental profile is limited? How can this inform standards, procurement, and deployment models?

LOCATION

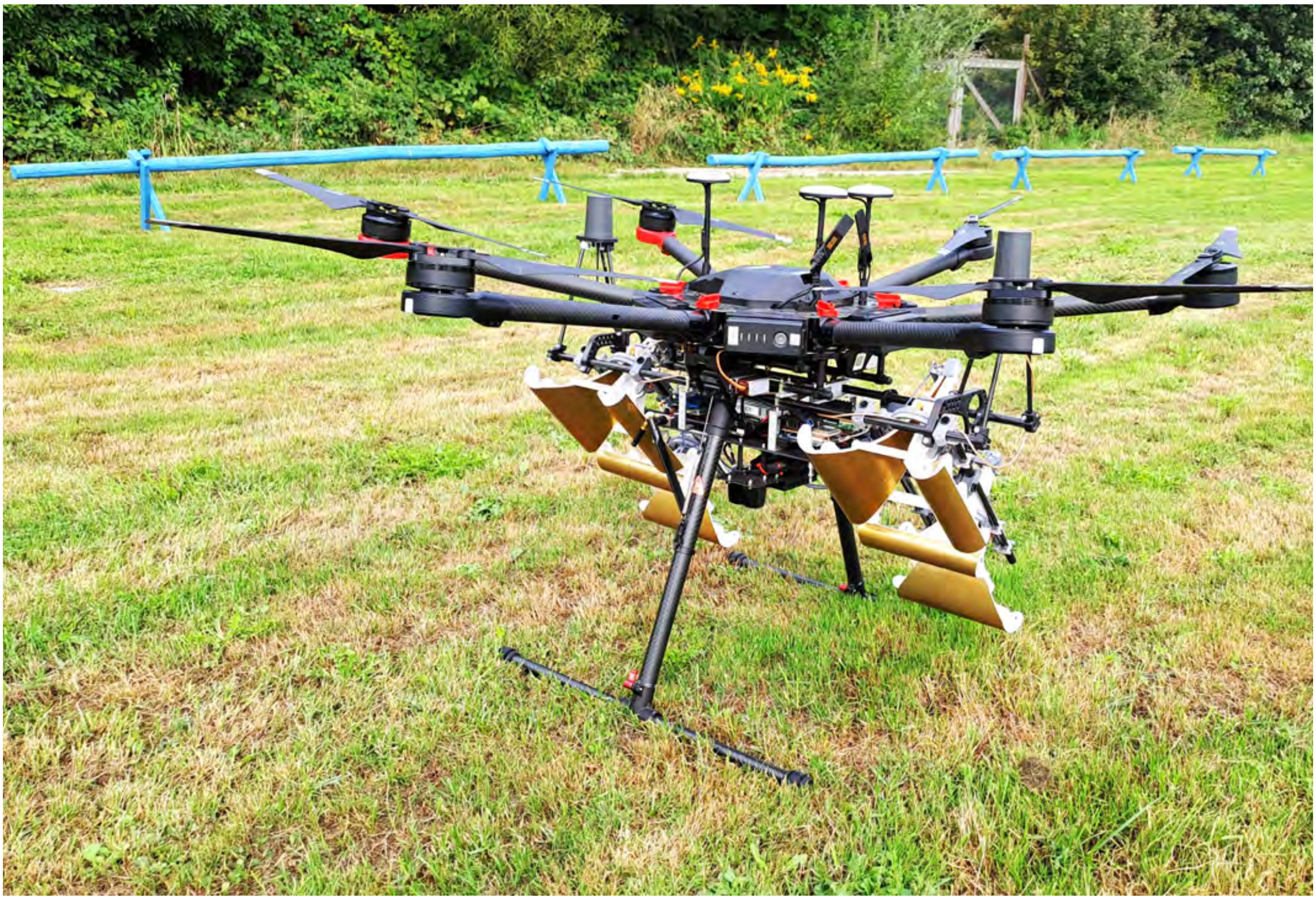
Challenges in accurately determining the boundaries of explosive ordnance contamination can lead to the over- or underestimation of hazardous areas. This can divert clearance resources to explosive ordnance-free areas or leaves contaminated land insufficiently addressed, thus undermining the efficiency, effectiveness, and safety of land release.

The quality of evidence indicating the presence or absence of EO is a critical factor for the efficient allocation of resources throughout the land release process. Evidence collection is a continuous process, and the resultant boundaries are reassessed when new information arises. Thus, limited or inaccurate data may result in over- or underestimation of contamination. When boundaries are drawn too broadly due to limited evidence, large areas may be classified as hazardous without confirmation, triggering unnecessary survey and clearance activities and increased time and cost. Conversely, when boundaries are defined too narrowly, contamination may extend beyond the designated area, creating safety risks, potential residual contamination, and reputational consequences. NTS relies mostly on community information, which can fade over time as populations displace or move. TS relies on more costly and slower processes involving manual, mechanical, and/or ADS. Without reliable and verifiable data, operational decisions often revert to costly full clearance methods, sometimes in safe land, to provide acceptable confidence levels.

Each method–manual, mechanical, or ADS–has operational limitations depending on environmental conditions. Machines are difficult to deploy in steep areas or dense forests, while ADS detection capacities are impacted by wind, heat, humidity, or animal fatigue. Yet, both require substantial logistical support, which can limit their operational flexibility. Manual deminers continue to rely on detection tools, such as metal detectors and prodders. In damaged urban areas–such as collapsed buildings, rubble, reinforced concrete, and heavy metal clutter–the limitations become even more severe.



Mechanical demining assets are important for technical survey and clearance. In Bucha, Ukraine, a remote-controlled Bozena-5 equipped with flails (Ukraine Demining Services - UDS) conducts systematic technical survey, assisted with uncrewed aerial vehicle (UAV) for remote control visualization by operator. © GICHD 2025



Uncrewed aerial vehicle (UAV) - based remote sensing capacities have progressed significantly in recent years, but further testing and evaluation is needed for them to prove impactful. UAV equipped with Ground Penetrating/Synthetic Aperture Radar (GP/SAR) in test field, Ulm, Germany. © GICHD 2025

The use of remote sensing in NTS and TS, including geospatial analysis of satellite imagery and the deployment of UAV-based sensing technologies, was recently incorporated into IMAS 07.11 on land release and offers significant potential to improve the accuracy of hazardous area delineation. However, technical and regulatory gaps may hinder their wider field adoption. Some of the reported challenges of deploying remote-sensors in land relaase, in addition to vegetation density or visual obstacles, include the following:

- A lack of commonly accepted testing and evaluation protocols for these technologies makes it difficult for NMAAs to authorize them, slowing adoption and limiting targeted research and development. The structural lags between rapid technological innovation and the slower processes of methodology validation, and standardization hinder the rapid integration of technologies into land release processes.

- Emerging sensors are often assessed primarily on their stand-alone technical performance, reflecting an imbalance between technical advancement and application approaches. Limited investment has been made in testing how these tools can be effectively integrated into operational procedures and the best ways to utilize them.

- EO-impacted countries often face infrastructure deficits, including limited geographic information systems (GIS) capacity, weak telecommunications networks, and a shortage of qualified personnel to operate some of these new technologies.

- UAV-based sensors are subject to signal degradation at higher operating altitudes and may experience interference from surrounding terrain or weather conditions.

- Remote-sensing data storage and analysis is complex and resource-intensive, and requires specialized skills, additional software, a structured methodological approach, and adequate integration into information management systems, increasing operational complexity and cost.

- Effective application of satellite imagery is constrained by challenges in establishing trusted, AI-assisted analysis methods to identify evidence of contamination, as well as practical barriers to data access, user capacity, and integration with national standards and information management systems.

Integrating UAV platforms equipped with various sensors into survey processes has significant potential to support the evidence-based location of EO, by direct detection or indirect evidence of possible contamination. While most commonly deployed UAV-based surveys focus on surface contamination, these systems can overcome the physical constraints of manual processes by providing rapid, wide-area assessments and high-resolution topographic mapping capacities. Remote sensing can enable accurate boundary delineation and corroborate unreliable or incomplete historical data by enhancing data collection and identifying terrain features relevant to contamination. This, however, requires robust methods to analyse and interpret the large volumes of data they generate. The limitation of reliably estimating subsurface contamination for the accurate definition of SHA/CHA remains.

As with detection technologies, AI-assisted multiple-sensor data fusion shows promise. Its effectiveness, however, depends on the availability of centralized, high-quality, ground-truth datasets; verified data collected directly from operational contexts; and used to train AI models.

Annex-A of this document provides a non-exhaustive overview of key detection and location technologies based on their relevance to land release operations, their current or potential applications, and their prominence in stakeholder consultations and recent literature.

Research questions

1. What standardized protocols and criteria are required to integrate digital remote-sensing data into existing land cancellation and reduction processes?
2. What methodological, quality assurance, and accreditation mechanisms are needed to ensure that remote-sensing survey outputs provide credible evidence to support land release decisions in accordance with "all reasonable effort" principles and criteria?
3. How can predictive analytics integrate historical conflict data, survey records, satellite imagery, and sensor outputs to generate evidence-based models that improve the identification and boundary definition of hazardous areas?
4. How can electro-optical and other remote-sensing systems be integrated into NTS and TS to improve accuracy, efficiency, and safety?
5. How can appropriate UAV platforms and associated sensors be optimally matched across different specific terrain types, environmental conditions, and EO contamination types to enhance evidence generation, boundary definition, cost-efficiency, and effectiveness in land release?

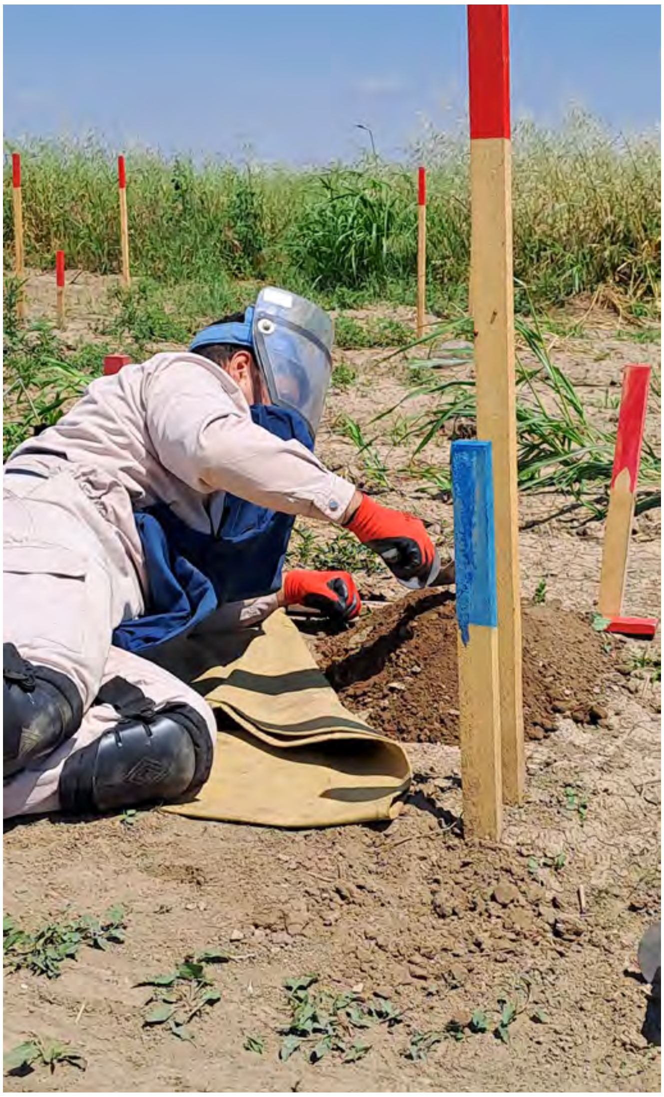
EXCAVATION

Manual excavation of signals in landmine technical survey and clearance is a slow and highly risky task for deminers.

Typically, during clearance operations, each signal detected by a metal detector is investigated through excavation, unless it can first be resolved through simpler means, such as visual inspection, brushing, or magnets used to exclude non-explosive metal clutter. Manual excavation remains the standard method used to investigate detector signals during clearance operations, with millions of manual excavations carried out each year. Most of the fatalities between 1977 and 2024 reported by operators to the online central repository of accidents, incidents, and near misses MACRA system, happened during manual signal investigations.[21] It is also the task during which deminers must work closest to the EO, at distances where protective equipment becomes less effective. Certain operational conditions further increase the risk: dense vegetation, tripwires, and booby traps are typical challenges that can compound with the soil types and weather conditions.

Mechanical assets are already integrated in land release, particularly for ground preparation and verification, but recent trials of micro-excavators and robotic compressed air excavation systems provide a possible new approach. However, affordable stand-off excavation systems remain limited, not widely available, or insufficiently developed to meet the operational requirements of different contexts. In addition, the deployment of mechanical assets and stand-off robotic systems can be constrained by terrain accessibility, cost, logistics, and maintenance requirements.

Minimizing the need for, and number of, manual excavations can make clearance both faster and safer, while also enabling operational performance, including longer effective working time and higher productivity.



Manual excavation of signals in technical survey and clearance is a slow and highly risky task for deminers. A demonstration of manual excavation technique in Aghdam, Azerbaijan (ANAMA).

Research questions

1. How can stand-off excavation systems be optimized or semi-automated, according to the type of EO, to improve precision and control, while keeping operator training requirements minimal and efficient?

2. How can stand-off excavation systems be designed to remain cost-efficient, robust, and simple to repair and maintain in remote operational environments with limited technical support?

3. What simple, affordable excavation tools and techniques (including modified hand tools, mechanical assists, or locally developed solutions) can provide measurable safety and efficiency improvements, while minimizing personnel's exposure to risk, in resource-limited programmes or environments?

4. How do different soil types affect excavation difficulty and risk, and what context-specific tools and techniques can improve safety and efficiency under varying soil conditions?

5. How can real-time sensor data be used to improve excavation planning by providing better information on target depth, object characteristics, and surrounding conditions before excavation begins?

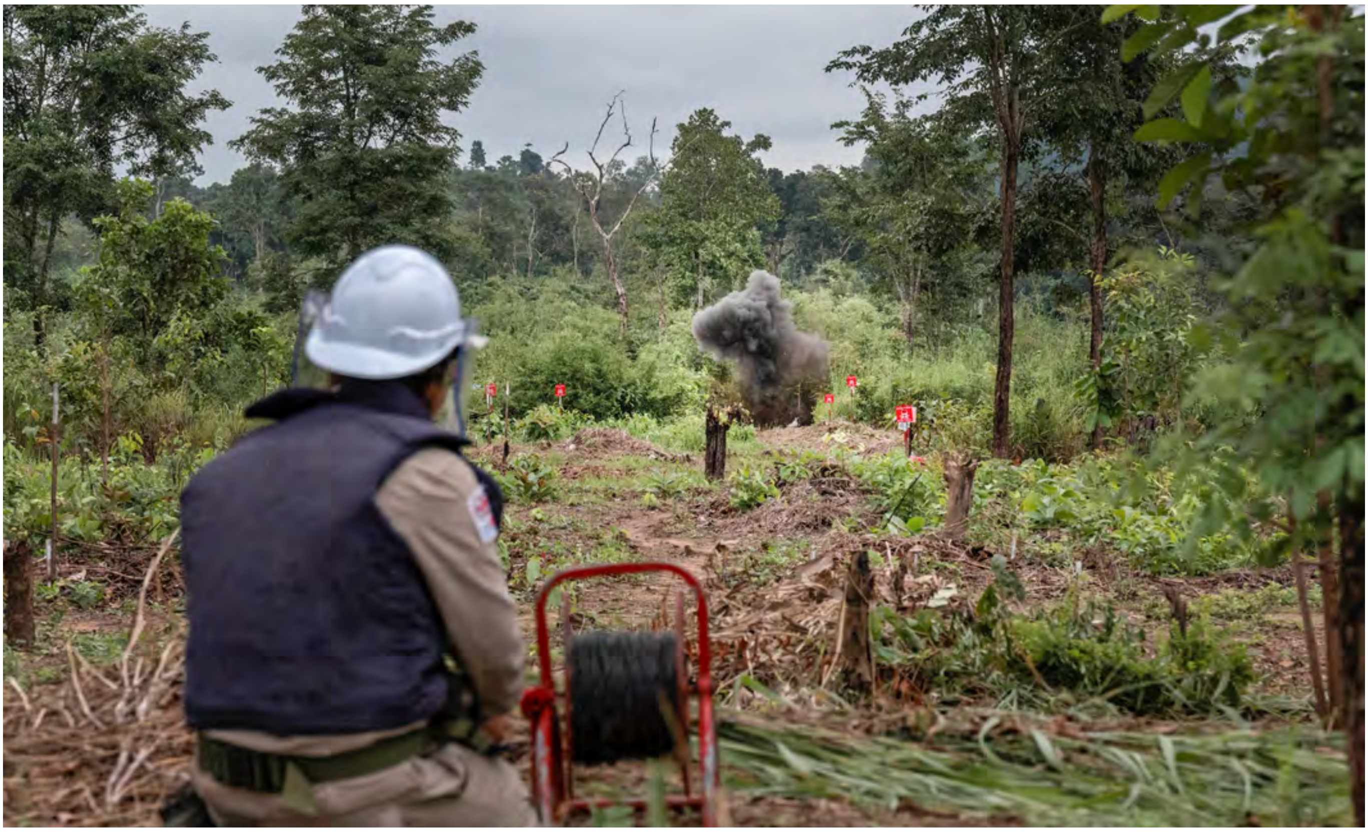
DISPOSAL

Disposal of explosive ordnance relies primarily on controlled demolition, whether of single items or in bulk, which creates significant safety, environmental, and logistical challenges.

Unsafe-to-move EO is typically disposed of in the place where it was found, through demolitions with donor charges. Safe-to-move items are generally transported, stored and disposed of in mass demolitions at controlled demolition sites. In both cases, this requires qualified EO disposal personnel responsible for the implementation of strict safety procedures for transport, storage, and handling of explosives, blast, and fragmentation protective measures, and adoption of safety distance cordons. Transport to, and storage in, controlled demolition sites require additional safety measures.

Preparation of blast and fragmentation protective works, such as sandbag pits or trenching, is a slow and resource-intensive activity, particularly when these need to be done manually. In populated urban areas and large safety distances perimeters, effectively controlling safety cordons can be challenging, representing additional risks for local communities.

In many operational contexts and national regulations, restrictions on access to explosives or a lack of explosives stocks limit or constrain access to explosive donor charges and licences to execute demolition of EO. In many cases, demolition requires the coordination with local national authorities, who assign national dedicated EO disposal (EOD) qualified personnel on a needs-basis.



Demolitions commonly takes place in situ where explosive ordnance items are found. Demolitions of not-safe to move items in urban areas carry additional risks to already damaged or vulnerable structures. Picture: A demolition of antipersonnel landmine in an open field in Cambodia. © MAG (Mines Advisory Group) 2022

Demolition in place of large EO items may need to be executed in or near populated urban areas or close to critical infrastructure. Beyond the risk to life and limb from blast and fragmentation, protective works may require extensive preparations and costs, and the detonation can produce additional damage to buildings, and endanger structures that communities rely on for shelter and livelihoods.

Demolition methods also increase the environmental impact of operations. Detonation releases toxic chemical residues (including heavy metals and explosive compounds like TNT, RDX, and magnetic particles) into the soil and groundwater, where they can persist for decades and contaminate drinking water sources, and affect the quality of the soil for future farming and agricultural activities. While the environmental impact of a single detonation may appear limited, cumulative residue loading from repeated disposal activities in the same location poses a documented risk. RDX, in particular, exhibits high mobility in groundwater and resistance to natural degradation, and has been detected in groundwater plumes extending significant distances from disposal sites.[22] Additionally, demolitions produce the dispersion of additional fragmentation, which can add to clutter and false alarm rates of detection systems.

Research questions

1. What non-detonation methods and technologies can be used to neutralize explosive substances contained in EO safely and in an environmentally sustainable manner?
2. What type of biological remediation methods and technologies could be used to diminish or desensitize explosive compounds of EO in situ? And how can they be applicable, practical, and effective for mine action operations?
3. Where demolition is needed, what remedial actions could be adopted to address environmental impacts?
4. Which standardized and rapidly deployable blast and fragmentation mitigation systems can effectively reduce impacts, evacuation safety distances, and risks to nearby populations and infrastructure?
5. What decision-support tools can be developed to enhance the planning of mass demolitions and the design of effective blast and fragmentation mitigation measures and safety protocols?

3. OTHER FACTORS AFFECTING EFFICIENCY AND EFFECTIVENESS OF LAND RELEASE

Beyond technical challenges, the efficiency and effectiveness of land release are also shaped by broader institutional and governance factors.

PRIORITY SETTING

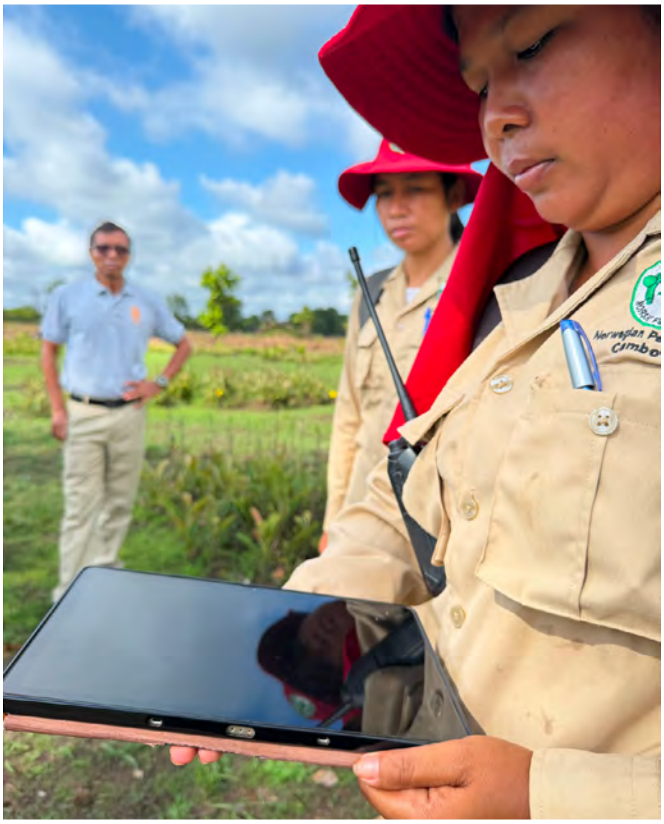
Priority setting remains a central challenge. NMAAs are responsible for determining where and when land release should take place in order to maximize humanitarian and development impact. However, in many programmes, prioritization systems remain weak. Limited whole-of-government engagement, inconsistent data collection, poor interoperability between systems, and an overreliance on simple output indicators–such as square metres cleared–often lead to suboptimal resource allocation. As a result, clearance efforts may focus on areas with limited socio-economic value while higher-impact locations remain unaddressed. Strengthening prioritization frameworks that combine operational data with socio-economic indicators and community needs would allow authorities to better direct resources and maximize impact.

GOVERNANCE AND REGULATORY FRAMEWORKS

Governance and regulatory frameworks often struggle to keep pace with technological change. Standards and guidelines may lack clear procedures for testing, verifying, and accrediting new technologies and/or methods. This creates uncertainty and institutional reluctance to adopt innovations, such as aerial survey data for evidence-based land cancellation or reduction. Administrative barriers–including lengthy approval processes, complex import procedures, and slow accreditation systems–can further delay the deployment of both existing and emerging technologies. Training systems increasingly struggle to keep pace with new technologies and methodologies, while mechanisms to capture and transfer operational knowledge remain limited.

INFORMATION MANAGEMENT AND DECISION SUPPORT

Information management systems also play a critical role. While systems (such as the information management system for mine action - IMSMA) provide a common framework, implementation inconsistencies frequently limit their full potential. Data are often treated primarily as a reporting requirement rather than as a strategic asset. Fragmented data structures and classification approaches can hinder analysis, learning across programmes, and evidence-based decision-making. Strengthening integrated data platforms and analytical tools could transform operational data into active decision support systems for planning, prioritization, and monitoring.



Information management technologies improved mapping of explosive ordnance contamination over the years, with digital data collection methods improving efficiency and data quality. In Ratanakiri, Cambodia, a team leader from Norwegian People's Aid monitors the location of her team members. © GICHD 2026

At the same time, innovation in mine action faces structural funding barriers. Short funding cycles and limited tolerance for experimentation make it difficult to test, scale, and sustain new approaches, particularly in a sector characterized by diverse operational contexts and relatively small markets.

All these factors influence how effectively land release systems function and highlight the importance of strengthening governance, data systems, capacity development, and innovation support alongside technical improvements. While critically important, these issues extend beyond the scope of the present research agenda and the questions outlined in this document.

4. THE WAY FORWARD

This research agenda is the product of a collaborative effort, bringing together the perspectives and expertise of NMAAs, mine action organizations, and technological and academic expertise through the Mine Action Innovation Hub. The challenges and research questions presented here reflect the needs of the sector and are grounded in field realities.

We invite all stakeholders–from academia and mine action practitioners to donors and national authorities–to use this agenda as a strategic vehicle to foster partnerships, align efforts, and mobilize resources. By working together to address these priority challenges, we can accelerate the development and deployment of solutions that make a meaningful difference for communities affected by explosive ordnance.

ANNEX A. SUMMARY OF KEY DETECTION AND LOCATION SENSORS AND TECHNOLOGIES

#	Sensor	Features and advantages	Limitations
Geophysical and radar sensors (surface and subsurface)			
1	**Electromagnetic induction (EMI),** commonly known as metal detectors.	– Primary manual demining tool in TS and clearance – Detects small ferrous and non-ferrous metal objects (including metallic IED components) through their electromagnetic response, typically to depths of up to 30 cm – Reliable, user-friendly, portable, lightweight, and affordable – Deployed in handheld detectors and in large-loop configurations for detecting large, deep-buried EO at greater depths – Used for surface and subsurface detection – The only detection system with dedicated test and evaluation protocols in the IMAS framework (Test and Evaluation Protocol 07.05/2003)	– High sensitivity produces high false alarm rates — up to 100:1 or higher — in cluttered or mineralized soils – Limited detection of low-metal EO; no detection of metal-free EO – Requires close proximity to the ground, as signal strength
2	**Ground-penetrating radar (GPR)**	– Detects subsurface anomalies through the dielectric contrast between a buried object and the surrounding soil – Detection depth depends on antenna frequency, soil conditions, and target size. Small targets such as APM are typically detectable at 30–50 cm with high-frequency antennas. Lower-frequency systems can detect larger EO at depths of several metres in favourable soils – Detects surface objects through vegetation cover, based on the same principle (dielectric contrast between surface objects and air) – Used for subsurface detection in amenable soils and for surface detection through vegetation – Deployed in cart-based, vehicle-mounted and UAV configurations. Synthetic aperture radar (SAR) processing can be applied to GPR data, particularly on UAV-mounted systems, to improve image resolution and target discrimination	– Penetration depth is reduced in conductive or wet soils – High false alarm rates, due to limited ability to differentiate EO from rocks, roots, and other subsurface heterogeneities – Requires expert knowledge for defining survey parameters, data processing, classification, and analysis – High cost of units, maintenance, and spare parts

3	**Synthetic aperture radar (SAR)**	– Detects surface anomalies and terrain features by synthesizing and combining radar pulses collected along the flight paths a moving platform (aircraft, UAV, or satellite) to simulate a large antenna achieving high-resolution imagery – Operates day and night and through cloud cover, unlike electro-optical sensors – Longer-wavelength systems (e.g., L-band) penetrate vegetation cover and, in exceptionally dry soils, can reveal shallow subsurface features – Effective for wide-area mapping of conflict-related indicators, such as trenches, craters, and soil disturbance patterns, invisible to optical sensors – Deployed on satellites, aircraft, and increasingly on UAV platforms	– Does not detect individual small EO, such as anti-personnel mines; resolution supports area-level indicators rather than item-level detection – Subsurface capability is marginal and limited to exceptionally dry, low-conductivity soils – Prone to false indications from unrelated terrain changes (agriculture, erosion, construction shadows) – Requires expert knowledge for the definition of survey parameters, data processing, classification, and analysis – Access to high-resolution data can be costly, and airborne flights require significant planning and resources
4	**Dual-sensor systems** (combining EMI/ GPR)	– Combines EMI and GPR to improve false alarm rates: the EMI sensor typically acts as the primary detector, while the GPR verifies target shape and characteristics to reject clutter – May improve detection of minimum-metal and non-metallic objects, as advanced algorithms fuse data from both sensors – Can reduce false alarm rates to around 40:1 under certain conditions – Deployed in handheld detectors and vehicle-mounted systems – Used for subsurface detection	– Requires complex signal processing and calibration for different terrain and soil conditions – Requires extensive operator training to interpret data – Bulkier and heavier than standard metal detectors – Up to ten times more expensive than standard metal detectors
5	**Magnetometer**	– Detects subsurface ferrous objects by sensing the local disruptions they produce in the Earth's magnetic field – Lightweight, versatile, and low cost; able to scan large areas efficiently – Highly effective for large, deep-buried ferrous EO, such as aerial bombs, detectable at considerable depth – Used for subsurface detection of large ferrous targets – Deployed in handheld systems, crewed carts, underwater towfish, and UAV platforms (including surveys over shallow water); also used in array configurations	– Ineffective for small items, such as most APMs, and for non-ferrous or non-metallic objects – Performance is degraded by ferrous clutter, magnetic soil anomalies, and geological interference – Signal strength drops rapidly with distance for all targets; in practice, small items are only detectable at very close range, while large ferrous masses remain detectable at greater distances and depths – Requires expert knowledge for the definition of survey parameters, data processing, classification, and analysis
Electro-optical sensors (surface)			
6	**High-resolution RGB cameras** (with computer vision and AI processing)	– Detect surface objects based on their visible appearance, by collecting high-resolution aerial imagery, typically from UAV-mounted cameras, and generating orthophoto maps – Widely used across the sector due to the increasingly low cost of off-the-shelf cameras and small UAV systems; support both planning and detection tasks – Imagery can be analysed manually or with AI computer vision and machine learning algorithms – AI-assisted analysis enables rapid, automated target recognition, quickly dismissing visual noise from non-targets and significantly increasing data processing speed – Deployed almost exclusively on UAV platforms for surface detection; accessible and adaptable – Collected imagery supports orthophoto mapping and tasking	– As with all electro-optical sensors, only effective for surface-laid objects; cannot detect buried EO – Limited capacity to identify partially hidden items; ineffective in poor visibility caused by weather, vegetation, or dust – Automated target recognition requires extensive datasets and machine learning model training, including for partially visible items – Application in clearance is limited by the geolocation precision of finds and the inability to locate subsurface or visually obscured objects

7	**Multispectral and hyperspectral sensors**	– Detect surface anomalies or objects based on their spectral signatures, by capturing imagery across multiple light bands, including visible and non-visible light (e.g., near-infrared, shortwave infrared) – Multispectral sensors capture a limited number of broad spectral bands; hyperspectral sensors collect hundreds of narrow, contiguous bands, allowing more precise identification of materials based on their unique spectral signatures – Highly effective, for example, in detecting vegetation stress caused by leaking explosive chemicals or identifying disturbed soil patterns invisible to the human eye – Particularly useful in detecting IED emplacement; can also be effective in locating plastic-cased EO or tripwires on the surface – Produce 2D maps of chemical and physical surface properties – Mostly deployed on satellites and UAVs, often combined with high-resolution RGB cameras; uncrewed ground vehicle (UGVs) and handheld applications are also possible.	– Cannot see through vegetation or beneath the soil surface; contribute to subsurface detection only indirectly, where disturbed soil patterns remain identifiable – Lower spatial resolution than RGB cameras, limiting the ability to discriminate targets from false alarms, including with computer vision techniques – Performance is heavily dependent on sunlight and clear weather conditions – Prone to false positives from natural environmental changes (e.g., seasonal variations in plant health) – Requires expert knowledge for the definition of survey parameters, data classification, and analysis, and sophisticated software to interpret complex spectral data – High cost, particularly for hyperspectral sensors, compared to RGB cameras or EMI handheld detectors
8	**Thermal infrared imaging**	– Detects surface anomalies or objects based on their heat signatures, by capturing the temperature contrast between EO or recently disturbed soil and their surroundings – Can detect surface temperature anomalies above shallow-buried EO in arid environments under certain conditions (weather, time of day) – Based on the same principle as multispectral sensing, but specifically captures long-wave or mid-wave infrared bands, which relate directly to an object's temperature – Shares similar strengths with multispectral sensors, while being considerably more affordable – Provides non-contact, non-intrusive, real-time heat maps of the surveyed area; particularly useful in detecting IED emplacement – Mostly deployed on UAVs, often combined with high-resolution RGB cameras	– Shares the general limitations of multispectral sensors – Highly sensitive to environmental conditions and the time of data collection, which affect the thermal contrast of objects; most effective shortly after soil disturbance or during periods of rapid temperature change, e.g., around sunrise and sunset – Lower spatial resolution than RGB cameras, limiting the ability to discriminate targets from false alarms, including with computer vision techniques – Requires sophisticated image processing and expert interpretation of heat maps
9	**Light detection and ranging (LiDAR)**	– Creates accurate, high-resolution 3D maps of terrain and surface features by emitting laser pulses and measuring their return time – Can detect ground structures, such as craters, trenches, and similar conflict-related features beneath partial vegetation cover, providing indirect evidence to support NTS – Highly effective for planning access routes around SHAs – Used primarily in NTS, where terrain features can provide relevant evidence of contamination – Deployed on crewed aircrafts, UAV or UGV platforms, or handheld scanners	– Does not detect EO itself, but rather the surface anomalies associated with its presence – Performance is affected by dense vegetation and weather (rain, fog); the ability to capture small details depends on sensor type and survey parameters – Requires expert knowledge for the definition of survey parameters, data processing, classification, and analysis

Explosive substances detection (surface and subsurface)			
10	**Nuclear quadrupole resonance (NQR)** or zero field magnetic resonance (MR)	– Detects explosives directly, through the chemical fingerprint of solid explosive compounds: a radio-frequency spectroscopy[23] technique identifies the unique molecular signature of explosives such as TNT or RDX – Unaffected by metallic clutter, and can therefore significantly reduce false alarms compared with metal detection – Particularly relevant for detecting minimum-metal EO and IEDs[24], since detection does not depend on metal content – Initial field trials have demonstrated the ability to detect RDX-based explosives, with the potential to speed clearance rates by up to 30% in current trials[25] – Fully portable and battery-powered – Currently envisioned as a secondary confirmation tool, verifying signals flagged by metal detectors and dismissing false alarms – Deployed in handheld configurations; vehicle-mounted systems have also been demonstrated	– Requires tuning to specific target compounds: detects known signatures, not explosives in general, and only works with crystalline (solid) explosive compounds – Metallic casings shield the explosive from detection – Highly sensitive to temperature variations, affecting reliability of results – Struggles with low signal-to-noise ratios, especially for TNT, which produces inherently weaker signals than RDX[26] and suffers higher radio-frequency interference from the environment[27] – Requires longer interrogation times per signal – Systems remain in early deployment stages; current development is optimized for RDX-based explosives, with further work needed for TNT detection
11	**Thermal neutron analysis (TNA)**	– Detects explosives directly, through a nuclear technique: neutrons emitted into the ground are absorbed by nitrogen atoms; a key component of most explosive substances, such as TNT and RDX, causing nitrogen to emit gamma rays with a unique energy signature that identifies the substance – Can detect explosives even within sealed metal casings, which do not significantly block neutrons or gamma rays. – Used as a confirmatory tool to verify suspected targets flagged by primary detectors – Deployed mainly in vehicle-mounted configurations as a confirmation sensor	– The weight of the neutron source, its shielding, and the detectors currently precludes handheld use; further development is needed for user-friendly, portable systems – Neutron radiation shielding is a key safety concern, requiring careful handling and licensing of radioactive sources – Requires advanced algorithms to distinguish explosive-related nitrogen signals from natural background interference, as nitrogen is also present in soils and fertilizers – Long measurement times per target compared with other confirmation methods

ENDNOTES

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15 Jacqueline MacDonald Gibson and J. R. Lockwood, 2003, *Alternatives for Landmine Detection* (Santa Monica, CA: RAND Corporation), https://www.rand.org/pubs/monograph_reports/MR1608.html. The article defines NQR as a radio frequency technique that can be used to interrogate and detect specific chemical compounds, including explosives. An NQR device induces an RF pulse of an appropriate frequency in the subsurface via a coil. The RF pulse causes the explosives' nuclei to resonate and induce an electric potential in a receiver coil. NQR is similar to MR but uses the internal electric field gradient of the crystalline material rather than an external static magnetic field to initially align the nuclei.

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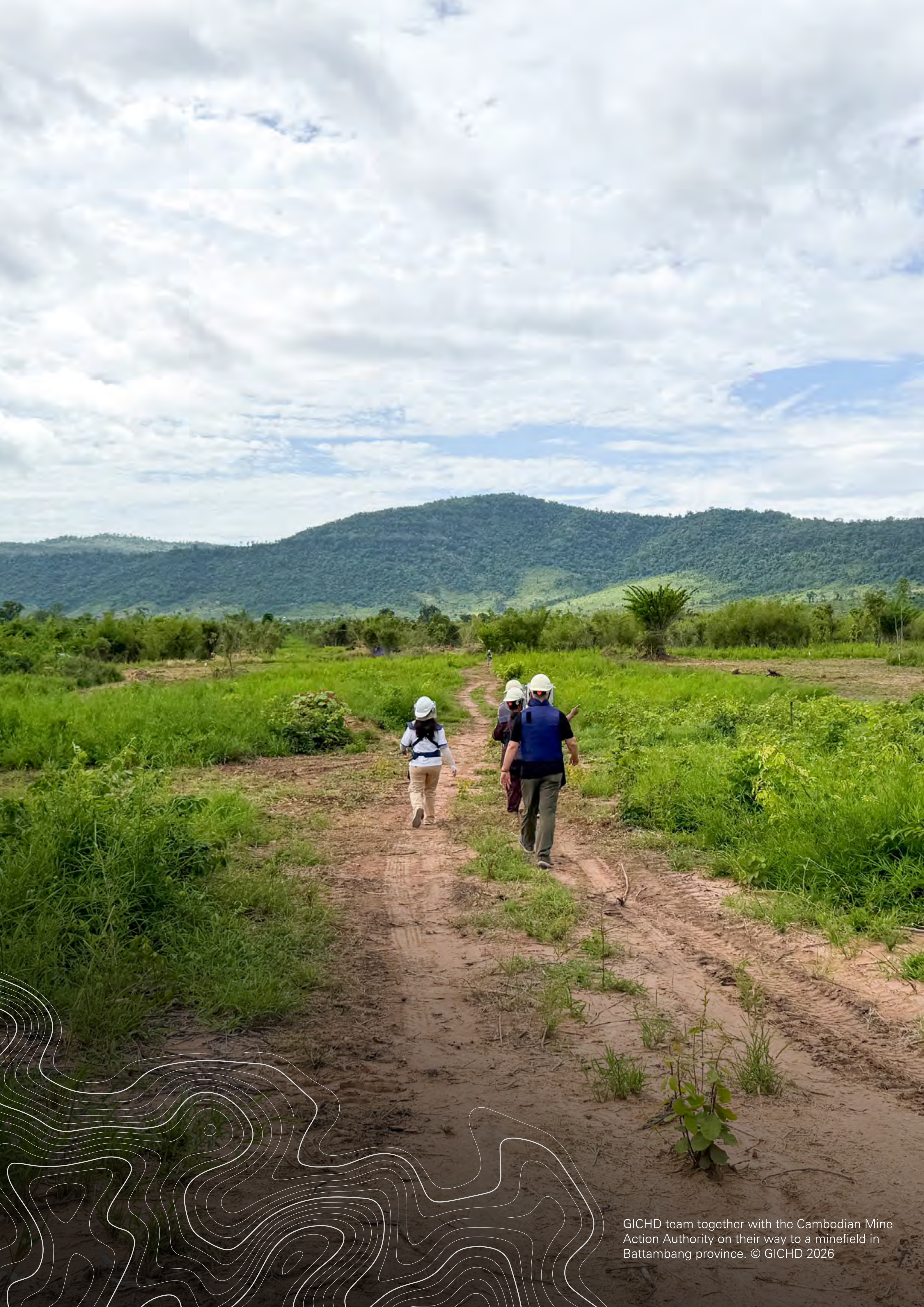

GICHD team together with the Cambodian Mine Action Authority on their way to a minefield in Battambang province. © GICHD 2026