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Risky Removal: Developing a Holistic Understanding of the Risks of Redeveloping Sites Contaminated with Unexploded Ordnance

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In the United States, approximately 10 million acres of public land have been used for live-fire military exercises and some fraction of the ordnance deployed here remains active and buried on site. As military facilities transition to civilian uses, unexploded ordinance (UXO) may endanger human lives or be buried on site. As military facilities transition to civilian uses, a fraction of the ordnance deployed here remains active and the United States government has invested considerable resources into finding and removing UXO. Using current techniques, magnetometers and electromagnetic induction sensors collect geophysical data to identify anomalies (metallic objects that might be UXO) and use signal-inversion and feature-extraction algorithms to infer likely, but uncertain, locations and material properties. Lacking clear decision guidance, risk-averse site managers often spend the majority of resources digging scrap metal with false-positive UXO signals, which is untenable given the vast scope of the problem and diverts scarce resources from higher-risk areas.

Despite sensor advancement, remediation managers face a series of difficult and nontransparent decisions regarding risk, cost, mission, and sociopolitical trade-offs. These decisions are often dealt with ad hoc and fall short of risk-informed guidance regarding when to remediate, where to prioritize digging, suitability for future uses, and residual risks. Even with extensive digging, it is difficult to know that all UXO have been removed, making questions like “can you guarantee that this site is safe?” and “how sure are you?” difficult to answer.

Intuitively, we understand that risk involves more than sensor data and signal processing. Given two similar sites with similar distributions of identified anomalies, would a site manager be equally confident that remediation had ensured future safety if (A) one site is intended for a wildlife preserve and the other for public use; (B) one site has an oral history of live ordnance and the other of predominantly inert ordnance use; or (C) one site is near many excavated UXO and the other near excavated scrap with false-positives signals? In each case, advanced classification technologies may not differentiate between the contrasted examples, yet a rational person would expect risks to differ. Rather than indicating a failure on the part of sensor technologies, this highlights the importance of including nonsensor information.

Bayesian Networks are particularly useful for transparently integrating diverse information to estimate probabilities. For example, suppose interviews, site histories, and geophysical information inform expert judgments about likely UXO concentrations. Experts define prior probability distributions (e.g., Beta distributions) for the proportion of UXO. Geophysical sensors provide additional information. Real-time excavation results update the distributions. Existing sensor analysis tools match the closeness between detected anomalies and object types. BNs can combine all these into predictive probabilities (Figure 1, left side). While BNs have occasionally been used in current classification efforts, they do not integrate dig results and rarely use data from nonsensor sources.

The probability of UXO existing at a site, as calculated by the BN, provides directly actionable input for risk analysts. These probabilities can be combined with estimates of human exposure, possible detonation, and expected consequences to quantitatively compare postremediation risks. Even after developing an understanding of expected loss, judgments are still needed about whether a site presents acceptable risk for use. At some sites, the remainder of even a single unexcavated UXO could be deadly, while at others, judiciously choosing to leave possible UXO may be worth the cost savings of not excavating thousands of anomalies unlikely to ever be encountered, enabling the remediation of additional sites (Figure 1, center).

A decision-analytic value model can further help by explicitly and transparently facilitating trade-offs between the various risk and nonrisk (e.g., cost, mission, stakeholder) criteria relevant for decision making. Here, impacts and benefits are evaluated and weighted along each category and aggregated to assess the holistic goodness of an outcome. Once we have estimated (A) the probability that an anomaly is live ordnance and (B) its expected contribution to various risk and nonrisk outcomes, it is possible to prioritize anomaly removal with respect to risk-informed, transparent, and holistic standards and thresholds. This provides decision support based on full consideration of inherent trade-offs between factors that directly reflect stakeholder and decision maker priorities, preferences, and values (Figure 1, right side).

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There are many benefits to this integrative BN, risk, and decision analytic approach. It is able to augment current limited or ad hoc uses of qualitative and secondary information (e.g., oral histories, site characteristics, expert judgments) to explicitly incorporate relevant information about likely UXO concentrations. It can also better characterize uncertainty and residual risk. For example, the language of Bayesian statistics facilitates simple statements about risk probabilities in a way that classical statistics (e.g., based on confidence intervals) does not, removing noise from the decision process at the junction between evidence and action. This approach also explicitly incorporates stakeholder and management values, providing improved decision support. By shifting focus from UXO presence to the more relevant end points of safety, environmental impact, and other decision criteria, site managers can better prioritize dig lists and manage risks given limited funding. In summary, by augmenting existing techniques with expanded analytical assessments, we recommend an approach site managers can use to more quickly and cost-effectively infer likely UXO concentrations and more transparently reach holistic, risk-based remedial decisions for the redevelopment of contaminated sites.

Figure 1. Proposed UXO-remediation decision support framework. A Bayesian Network integrates diverse information to better identify and classify UXO (left), risk analysis transforms UXO concentrations into more relevant risk-related outcomes (center), and decision analysis integrates risk-related outcomes with other important decision concerns to provide holistic decision support (right).

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Notes
The authors declare no competing financial interest.

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