Summary

No single soil property such as pH or percent soil organic matter best explained patterns of landmine functionality, particularly where we were able to quantify soil properties associated with functional and non-functional landmines of the same type (e.g., PMN, M14, M35). Nevertheless, this study shows that several soil properties appear promising as indices of environmental settings likely to be associated with rapid aging (degradation) of landmines, including very ‘high-level’ or ‘master’ soil variables such as pH (how acidic a soil is), texture (how sandy or clayey a soil is), and soil carbon. Furthermore, our results suggest several more ‘esoteric’ variables could also be useful in ‘fingerprinting’ landmine aging (e.g., soil carbon-to-nitrogen ratios (C:N) or levels of tin, antimony, or other trace elements used in the manufacturing of landmine components).

Goals

There were two goals of this study:

- **Characterization of soil properties** associated with landmine parts, with a particular focus on properties likely to influence corrosion or degradation;
- **Development of quantitative relationships between soil properties and landmine characteristics**.

Introduction

There seems to be a geophysical ‘gold rush’ underway in the handling of unexploded ordnance. Recent advances in geophysical technologies, for example, have been

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34 The terms ‘functional’ and ‘non-functional’ in application to landmine samples for this research do not mean the mines have been confirmed to work or not work. Rather, the terms represent samples that have been identified by technical experts during field review as likely to function as intended, or unlikely to function as intended. For mines unlikely to function as intended, this could mean a mine does not function at all, or else functions in a way different than intended—possibly more dangerous or possibly less dangerous. However, for the sake of this analysis we are focusing on mines unlikely to function as intended that are for practical purposes non-functional if activated by pressure.
celebrated for their abilities to detect unexploded ordnance.\textsuperscript{35,36} The promise of these technologies is that they will “distinguish between UXO and harmless objects,” an important accomplishment since “field experience indicates… in excess of 90% of objects excavated during a munitions response are found to be nonhazardous.”

While these geophysical approaches are certainly impressive in their abilities to distinguish composition (ferrous from non-ferrous metals, presumably based on k-wave returns), shapes, and depths of buried objects, the positive identification of UXO (or mines) based on ‘macro’ physical and chemical characteristics \textit{does not necessarily mean that functional UXO can be identified, or most importantly, that functional UXO can be distinguished from non-functional UXO.}

Such a quantum leap in UXO management requires models of explosive-remnants-of-war aging that incorporate both out-of-the-box vulnerability to degradation as well as environmental setting characteristics most likely to influence degradation, both in concert with geophysical advances. This coupling of landmine and soils characterization and geophysical techniques is not novel, but it does represent a more nuanced perspective than is evident in even quite recent research. For example, Preetz et al. (2007) suggest landmine detection with metal detectors is hampered in tropical lateritic soils.\textsuperscript{37} But \textit{how do aging landmines additionally or multiplicatively complicate detection}, in addition to complexities associated with soil properties?

A Scoping Study in 2008 examined the effects of aging on landmines in Cambodia and found that many types of landmines appear to cease functioning as intended due to processes associated with aging.\textsuperscript{38} This report summarizes research activity associated with the first phase of follow-up study, aimed at quantifying soil properties in the vicinity of landmines, and with an eye which was aimed at understanding the factors most likely to contribute to landmine aging. A keener understanding of these factors should assist in reprioritization of clearance efforts and direction for future R&D, leading to innovative solutions and efficiencies for mine action and clearance. Specifically, it is believed that findings may assist the development of more effective countermeasures, allowing some suspected hazardous areas to be more quickly released for use, and clearance resources to be diverted to more appropriate areas, in addition to catalyzing new R&D efforts.

Aging of landmines involves the chemical weathering and physical breakdown of the numerous components that comprise a typical landmine. Because corrosion of metallic components is fundamentally driven by reduction-oxidation reactions, we targeted soil

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\textsuperscript{38} http://maic.jmu.edu/aging/aging_intro.html
properties and landmine characteristics that may help ascertain the relative importance of these types of reactions to aging processes.

**CONCEPTUAL MODEL**

We have approached the issue of landmine aging from a quantitative pedological perspective. Pedology is the study of soils, and at its marrow, addresses the question “Why do soils have the properties they do?” Traditionally, pedology has been largely descriptive, and dominated by efforts to map current soil properties. There are two fundamental tacks that can be taken: (i) a correlative approach, that summarizes ‘soil-forming factors’ thought to most strongly influence soil properties, and (ii) a process-based approach, where the underlying processes are defined and quantified.

The most popular factor approach suggests that soil properties (S) can be regarded as a function of a number of interacting factors. A process-based approach, by contrast, seeks to quantify processes that transform soils.

Raymond Siever (1974) first conceptualized these dynamics in an article “The steady state of the Earth’s crust”; William Schlesinger (1997) reformulated this central concept as:

\[
S(tn)=f(cl,o,r,p,t,h,\ldots)
\]

The ellipses hints at either interactions between these primary factors (e.g., cl x r) or additional factors.

The ocean is salty: acidity generated by micro- (and macro-) organisms and roots has attacked minerals that contain cations (salts) such as calcium (Ca\(^{2+}\)), magnesium (Mg\(^{2+}\)), sodium (Na\(^+\)), and potassium (K\(^+\)). In essence, hordes of H\(^+\) (acidity) bump salts into soil solution, from whence they travel to the lowest part of the planet, the ocean.

40 …such as climate (cl), biota (o), relief (r), parent material (p), time (t; but really duration of soil-forming processes), and human activities (h):
42 For example, precipitation in excess of evapotranspiration will generally increase soil moisture, and because soils host billions of living (‘respiring’ or carbon dioxide [CO\(_2\)]-producing) bacteria, moist soils act as blankets of acidity as water absorbs CO\(_2\) to produce carbonic acid (H\(_2\)CO\(_3\)), which, as with any acid, can split apart (dissociate) in solution to form H\(^+\):

\[
CO_2+H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-
\]

pH is a measurement of acidity, and is defined as the negative logarithm of the concentration of H\(^+\) (-log H\(^+\)); because of the negative sign, pH and acidity are inversely related. As pH increases, the concentration of H\(^+\) (acidity) decreases, and as pH decreases, acidity increases. Because of the logarithmic relationship, every 1 unit change in pH translates to a 10-fold increase or decrease in acidity. Thus, the average Cambodia pH (6.1) is ~32 times more acidic than the average Jordan pH (7.6).

Acidity, in turn, attacks primary minerals such as a granite or limestone bedrock, converting these ‘parent materials’ into secondary minerals. One consequence of this weathering is that the most mobile ingredients in parent material are unleashed from their mineralogical dungeon, whereupon they follow gravitational and hydrological pathways to their ultimate ‘base level’: the ocean. This is why the oceans are salty: acidity generated by micro- (and macro-) organisms and roots has attacked minerals that contain cations (salts) such as calcium (Ca\(^{2+}\)), magnesium (Mg\(^{2+}\)), sodium (Na\(^+\)), and potassium (K\(^+\)). In essence, hordes of H\(^+\) (acidity) bump salts into soil solution, from whence they travel to the lowest part of the planet, the ocean.

igneous rock + acid volatiles $\rightarrow$ sedimentary rocks + salty oceans

The research team reformulated this as the ‘salty ocean equation’—a fundamental organizing principle for understanding chemical weathering and, by analogy, landmine aging, in soils.

$$\text{parent material} + \text{H}_2\text{CO}_3 \rightarrow \text{clays} + \text{salty oceans}$$

A pedological approach to landmine aging, therefore, is the substitution of landmines for parent material. This approach seeks a process-based, rather than empirical, predictive model for the trajectory of landmine functionality.

**METHODS**

**Physical sample collection and transfer to JMU Soils Lab.** Personnel affiliated with the Center for International Stabilization and Recovery sampled 16 locations for both soils and associated landmine parts in the ‘K-5’ belt of Cambodia in November 2009; an additional 10 locations were sampled for soils and associated landmine parts in northern Jordan in May 2010. Numerous georeferenced photographs were obtained. In total, 33 soil samples were collected for transport to the James Madison University (JMU) Soils Laboratory under USDA Permit #P330-09-00212, reproduced in *Figure 1*. In this report, we focus on those 26 samples for which soils and landmine parts were obtained simultaneously.  

Cambodia samples generally were sourced from two locations: 13.56°N, 102.41°E and 13.59°N, 102.57°E. Jordan samples were also generally sourced from 2 locations: 32.54°N, 36.08°E and 32.51°N, 36.20°E. Using the georeference data collected by the field researchers, soil/mine sample locations were then overlaid onto available maps identifying soil types, as seen in *Figures 2 and 3.*

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45 While 33 soil samples were collected for research, only 26 intact soil-landmine sample pairs were transported to James Madison University because some mines were deemed too high risk to move or study further or were unable to be safely defuzed. Specifically, no landmine components were characterized for Cambodia soil samples C11 and C16, or for Jordan soil samples J2, J3, J5, J6, or J14, so we do not present the corresponding soils data in this report.
**Figure 1.** USDA Permit for soil transport to James Madison University.

**Figure 2.** World Reference Base soil map units associated with Cambodia (outlined in blue). Soils and landmines were collected from the northwestern corner of the country, in soils mapped as “Acrisols, Alisols, and Plinthosols (AC).”
Figure 3. World Reference Base soil map units associated with Jordan (outlined in blue). Soils and landmines were collected from the northern part of the country, in soils mapped as “Leptosols and Regosols (LP).”

Research methods undertaken at JMU Soils Lab. Upon receipt in the laboratory, all samples were air-dried and sieved at 2 mm. All further mentions of soil refer to <2-mm material. In one instance, a Jordan rock sample was discovered during sieving. This sample was analyzed to assess the chemical differences between the soil associated with the landmine and the soil’s ‘parent material.’

The research team characterized 9 soil properties as part of this study (Table 1). Coefficients of variation (CV), used to quantify the variability of a procedure by dividing the standard deviation of duplicate results by the average result, were calculated as well.

Soil pH was measured by adding 10 ml of distilled water to 10 g of air-dry soil, stirring, allowing to sit for 30 minutes, and then inserting a calibrated, handheld pH electrode into the supernatant. For pH, CVs ranged from 0 to 2%.

Electrical conductivity was measured using a calibrated, handheld electrode in the same supernatant as pH; CVs ranged from 3-34%.

Soil texture was measured using a hydrometer on a mixture of 40 g of soil and a dispersant/deflocculant to break soil particles apart (sodium hexametaphosphate/sodium carbonate). Soils were pretreated with ~30% hydrogen peroxide. CVs for sand, silt, and clay were 13, 6 and 21%, respectively.
**Table 1.** Summary of soil properties measured.

<table>
<thead>
<tr>
<th>Property</th>
<th>Rationale</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>index of soil acidity</td>
<td></td>
</tr>
<tr>
<td>electrical conductivity (EC)</td>
<td>index of soil salinity</td>
<td>deciSiemens per cm (dS/cm)</td>
</tr>
<tr>
<td>texture</td>
<td>index of water-holding capacity</td>
<td>percent sand [2 mm&gt;particles&gt;0.05 mm], percent silt [0.05 mm&gt;particles&gt; 0.002 mm], and percent clay [0.002 mm&gt;particles] by hydrometer</td>
</tr>
<tr>
<td>color</td>
<td>index of organic matter and clay content</td>
<td>Munsell color chart: hue value/chroma</td>
</tr>
<tr>
<td>soil organic matter (SOM)</td>
<td>essential precursor for generation of biological acidity</td>
<td>percent; assumed equal to loss of weight upon combustion</td>
</tr>
<tr>
<td>total soil carbon &amp; nitrogen</td>
<td>the ratio of C to N can index microbial activity</td>
<td>percent</td>
</tr>
<tr>
<td>base saturation</td>
<td>index of soil acidity</td>
<td>centimoles of positive charge per kilogram of oven-dry soil (cmol+/kg-1)</td>
</tr>
<tr>
<td>‘major’ elements</td>
<td>composition of soil</td>
<td>typically percent</td>
</tr>
<tr>
<td>‘trace’ elements(^{46})</td>
<td>composition of soil</td>
<td>typically parts per million by weight</td>
</tr>
</tbody>
</table>

We also used the soil textures to derive a number of additional soil properties, including:
- Bulk density (an index of organic matter content, g cm\(^{-3}\))
- Saturated hydraulic conductivity (a measure of how quickly water can move through soil; m sec\(^{-1}\))
- Saturation (a measure of soil pore space; cm\(^3\) cm\(^{-3}\))
- Field capacity (a measure of soil-retained water after gravitational drainage; cm\(^3\) cm\(^{-3}\))
- ‘Wilting point’ (a measure of soil-retained water at 1.5 megapascals [MPa] of pressure; cm\(^3\) cm\(^{-3}\))
- Plant available water (measured as the difference between field-capacity and ‘wilting point’ moisture; expressed in centimeters)

**Soil colors** are typically expressed as hue, value and chroma. Value and chroma CVs were 0-47%. These relatively high CVs occurred because the difference between paint chips with chroma 1 and 2 is the standard deviation (0.71) divided by the average (1.5).

Hues correspond to a specific wavelength region of the visible part of the electromagnetic spectrum and can be calculated using a color book such as the Munsell color book (Figure 4).\(^{47,48}\) CVs for hues were 0% because all hues were 10YR (‘yellow-red’).

\(^{46}\) Typically, ~80% of soils derived from igneous rocks is comprised of SiO\(_2\), Al\(_2\)O\(_3\), and Fe\(_2\)O\(_3\), but we expected trace elements might enable us to learn more about the ‘aging process’.
Soil organic matter was assumed to equal the percent loss-on-ignition (LOI), which was calculated by measuring the weight loss in a departmental muffle furnace (6 hrs at 400°C) after oven-drying the soil samples to constant weight (typically 24 hrs at 105°C); 6 minutes in a microwave suffices for typical air-dried soils to obtain ‘constant weight.’

The research team used the equation:

\[ \text{%LOI} = 100 \times \frac{\text{post-microwave weight [wt]} - \text{post-furnace wt}}{\text{post-microwave wt}} \]

CVs for LOI ranged from 0-33%, averaging 10%.

Total carbon and total nitrogen were obtained by shipping samples to the Ecosystems Analysis Laboratory at the University of Nebraska Lincoln (http://www.biosci.unl.edu). CVs for total carbon ranged from 5-11%, while CVs for total nitrogen ranged from 0-9%.

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Footnotes:

47 Hues correspond to a specific wavelength region of the visible part of the electromagnetic spectrum and are indicated in the upper right hand corner of the right hand page (e.g., 10YR, for ‘yellow-red’); value is read on the vertical axis and is an indication of the saturation of color, higher values being lighter and lower values being darker (e.g., 4/6); and chroma is read along the horizontal axis and is an indication of the purity of color, with lower chroma associated with grayer colors (e.g., 4/6). A very readable introduction to color in general is Ball 2001: 24-49.

Base saturation measurement CVs typically are <20%. These cations were extracted from representative 1-g soil samples using 20 ml of 1 M ammonium acetate (NH₄O(C₂H₃O)); samples were shaken vigorously for 1 hr, and then allowed to sit for ~23 hrs before extraction on a vacuum manifold.

Major and trace elements were analyzed by x-ray fluorescence (XRF; light gray) or inductively coupled plasma-mass spectrometry (ICP-MS; dark gray) by ALS Chemex, Reno, NV.

RESULTS

Landmine analyses. Detailed characterizations of landmines were performed by Dr. Johnson, Dr. Davies, and Mr. King. We highlight the potential importance of some of these analytical results in the discussion section. Although 33 landmine and/or soil samples were collected in total and analyzed for this project, representing 10 different landmine types, this report focuses on the complete, matched 26 landmine/soil pairs for which landmines and soils were available and brought back to JMU (Table 2).

Table 2. Summary of numbers (total numbers/numbers used for soils analysis report) and vulnerability index values (in parentheses).

<table>
<thead>
<tr>
<th>Mine Type</th>
<th>Cambodia</th>
<th>Jordan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 72</td>
<td>2/2 (21)</td>
<td></td>
</tr>
<tr>
<td>Type 72</td>
<td>4/4 (21)</td>
<td>6/5 (17)</td>
</tr>
<tr>
<td>M14</td>
<td></td>
<td>2/0 (19)</td>
</tr>
<tr>
<td>M15</td>
<td></td>
<td>2/1 (8)</td>
</tr>
<tr>
<td>M19</td>
<td></td>
<td>4/3 (16)</td>
</tr>
<tr>
<td>M35</td>
<td></td>
<td>1/1 (*)</td>
</tr>
<tr>
<td>MK5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMD-6</td>
<td>3/3 (27)</td>
<td></td>
</tr>
<tr>
<td>PMN</td>
<td>8/6 (19)</td>
<td></td>
</tr>
<tr>
<td>PMN-2</td>
<td>1/1 (21)</td>
<td></td>
</tr>
<tr>
<td>Grand Total</td>
<td>18/16</td>
<td>15/10</td>
</tr>
</tbody>
</table>

* No vulnerability index value was assigned.

As Table 2 shows, no landmines complete with accompanying soil were encountered in both countries during this phase of research. The research team concluded that having overlapping, identical landmine types would have helped in the interpretation of factors likely to influence landmine aging.

49 In the previous Scoping Study as well in anecdotal, support research conducted in the Falkland Islands and other places, landmines were studied that overlap between the countries; however, these samples had no soil collected with them and therefore could not be included for the soils analysis research.
The greatest number of landmines were of the PMN type (8/33), which was assigned a vulnerability index (VI)\textsuperscript{50} value of 21 (Table 2). Of the 10 different mine types, VI values ranged from 8 (the antitank M19, collected from Jordan) to 27 (the antipersonnel PMD-6, collected from Cambodia).

Of the 6 PMN landmine/soil pairs assessed in this study, half were deemed capable of functioning as intended, based on an evaluation of fieldnotes recorded upon collection of the landmine sample.

**SOIL PROPERTIES**

Cambodia soils contained more soil organic matter (7.8%, see Figure 5) and had a lower pH (6.1; see Figure 6) than Jordan soils (4.2% and 7.6%, respectively). These patterns were reflected in soil colors, which we summarized by dividing the Munsell chroma by the Munsell value. Average Cambodia soil chroma/value were 0.7 (darker), whereas average Jordan soil chroma/value were 1.5 (brighter).

Specific calculations combining soil property characteristics for macro analysis were also conducted. Figure 5 shows the comparison of soil organic matter (%) between Cambodia-only, Jordan-only, and combined (C+J) soils in relation to the field estimates of whether the target landmines might be capable of functioning as intended: *Yes*, probably capable of functioning as intended; *No*, probably not capable of functioning as intended; or *Maybe*, no clear conclusion of functionality could be determined from field assessment.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{soil_comparison.png}
\caption{Comparison of soil organic matter (%) between Cambodia-only, Jordan-only, and combined (C+J) soils.}
\end{figure}

\textsuperscript{50} For discussion on vulnerability index, see Section 6, “Moving Beyond: Vulnerability Tools, Extrapolation and Final Analysis” and Annex J, “Full Summary of Report on Models.”
Figure 6 also depicts a paired comparison for three landmine types (M14 and M35 from Jordan, PMN from Cambodia) of associated soil properties, between samples identified as likely to function and samples likely to not-function as intended. Average soil organic matter (%), pH, and EC (dS m\(^{-1}\); /200) (±1SE) for were measured for:

- non-functioning (yellow dotted; n=1) and functioning (red; n=9) M14 landmines (Jordan)
- non-functioning (yellow dotted; n=2) and functioning (red; n=2) M35 landmines (Jordan)
- non-functioning (yellow dotted; n=3) and functioning (red; n=5) PMN landmines (Cambodia)

These analyses suggest an important interaction between country or climate and soil properties. The two non-functioning Jordan landmines (M14 and M35) had higher soil organic matter and slightly higher EC, whereas the non-functioning Cambodia landmine (PMN) had lower soil organic matter and EC, although in all cases, the variance within a specific landmine category was greater than the difference between functioning and non-functioning landmines. Only minor differences were noted in pH between functioning and non-functioning landmines.

For two of these three mine types, landmines that were determined to no longer function as intended were associated with more acid soils, although the largest average difference was only 0.5 pH units. For the M14 landmine, this greater acidity was associated with greater soil organic matter (6.0 vs. 3.7%) surrounding non-functioning landmines, whereas for the PMN landmine, the non-functioning landmines were found in soils with slightly lower soil organic matter (8.2 vs. 9.2%). Soils adjacent to non-functioning Jordan landmines had slightly greater EC, but those adjacent to non-functioning PMN landmines had slightly lower EC.
Figure 6. Three comparisons of mine type (M14, M35, PMN) measurements (soil organic matter, pH and EC) by functionality.

Additional comparisons between mines identified as potentially functional and non-functional were generated using a variety of soils analyses to look for significant differences. Figure 7 shows some of these comparative results for PMN, M14 and M35 samples.
Figure 7. Additional analyses conducted to compare functional v. non-functional mines (PMN, M14, M35) for differences
Additionally, all six types of landmines were analyzed in larger-scale groupings by type and based on whether they generally were found to function or not function. Half of the six mine types (Type 72, M15 and M19) were deemed to have samples capable of functioning as intended during field analysis. For this subset, soil organic matter levels were higher in soils surrounding non-functioning landmines and pH levels were lower, although EC values generally overlapped for soils surrounding functioning and non-functioning landmines (Figure 8).

As Figure 9 shows, consistent with the soil organic matter trends, Cambodia soils were finer-textured (17% sand) than Jordan soils (35% sand). Jordan soils contained twice as much silt as Cambodia soils, consistent with the climate and proximity to loess-generating areas. The greater clay content of the Cambodia soils is consistent with prolonged chemical weathering under a hot and moist climate.

These textural differences led, in turn, to nearly 4x-higher estimated hydraulic conductivities (the rapidity with which water can move through soils) for Jordan soils vs. Cambodia soils (0.66 vs. 0.17 cm sec⁻¹; Table 3).

Soil ECs were similar (Cambodia: 560±60 dS cm⁻¹; Jordan: 630±40 dS cm⁻¹).
Figure 9. Comparison of average soil textures for Cambodia and Jordan soils.
Table 3. Derived soil moisture properties for soils associated with different landmines. M14(N) refers to a ‘non-functioning as intended’ M14 landmine, whereas M14(Y) refers to a ‘likely to function as intended’ M14 landmine; mines estimated to be capable of functioning as intended are highlighted in green.

<table>
<thead>
<tr>
<th>Mine Type</th>
<th>Type 72</th>
<th>M14 (N)</th>
<th>M14 (Y)</th>
<th>M15</th>
<th>M19</th>
<th>M35 (N)</th>
<th>M35 (Y)</th>
<th>MK5</th>
<th>PMD-6</th>
<th>PMN (N)</th>
<th>PMN (Y)</th>
<th>PMN-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent sand</td>
<td>18</td>
<td>25</td>
<td>22</td>
<td>23</td>
<td>22</td>
<td>25</td>
<td>26</td>
<td>21</td>
<td>24</td>
<td>14</td>
<td>13</td>
<td>28</td>
</tr>
<tr>
<td>Percent clay</td>
<td>58</td>
<td>25</td>
<td>31</td>
<td>33</td>
<td>33</td>
<td>36</td>
<td>31</td>
<td>33</td>
<td>54</td>
<td>66</td>
<td>63</td>
<td>51</td>
</tr>
<tr>
<td>Percent silt</td>
<td>24</td>
<td>50</td>
<td>47</td>
<td>44</td>
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<td>43</td>
<td>46</td>
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</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
<td>1.21</td>
<td>1.35</td>
<td>1.31</td>
<td>1.3</td>
<td>1.3</td>
<td>1.29</td>
<td>1.32</td>
<td>1.3</td>
<td>1.23</td>
<td>NA</td>
<td>NA</td>
<td>1.25</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity</td>
<td>0.19</td>
<td>0.66</td>
<td>0.43</td>
<td>0.37</td>
<td>0.38</td>
<td>0.3</td>
<td>0.4</td>
<td>0.38</td>
<td>0.17</td>
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<td>NA</td>
<td>0.16</td>
</tr>
<tr>
<td>Saturation</td>
<td>0.54</td>
<td>0.49</td>
<td>0.51</td>
<td>0.51</td>
<td>0.51</td>
<td>0.51</td>
<td>0.5</td>
<td>0.51</td>
<td>0.54</td>
<td>NA</td>
<td>NA</td>
<td>0.53</td>
</tr>
<tr>
<td>Field capacity</td>
<td>0.47</td>
<td>0.3</td>
<td>0.33</td>
<td>0.34</td>
<td>0.34</td>
<td>0.35</td>
<td>0.33</td>
<td>0.34</td>
<td>0.44</td>
<td>NA</td>
<td>NA</td>
<td>0.42</td>
</tr>
<tr>
<td>Wilting point</td>
<td>0.34</td>
<td>0.14</td>
<td>0.17</td>
<td>0.18</td>
<td>0.18</td>
<td>0.2</td>
<td>0.17</td>
<td>0.18</td>
<td>0.31</td>
<td>NA</td>
<td>NA</td>
<td>0.29</td>
</tr>
<tr>
<td>Plant available water (cm)</td>
<td>0.14</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.15</td>
<td>0.15</td>
<td>0.16</td>
<td>0.13</td>
<td>NA</td>
<td>NA</td>
<td>0.13</td>
</tr>
</tbody>
</table>

NA: Not applicable; algorithm does not encompass such clayey textures.

In addition to these characteristics, many which can be easily quantified or estimated in the field (e.g., color, texture, pH, and EC), the research team analyzed Cambodia and Jordan soils for four exchangeable base cations (calcium [Ca\(^{2+}\)], magnesium [Mg\(^{2+}\)], potassium [K\(^{+}\)], and sodium [Na\(^{+}\)]). Additionally, the team also analyzed all soils for the total forms of these four cations, traditionally reported as percent oxides: CaO, MgO, K\(_2\)O, and Na\(_2\)O, respectively. Together, these four cations comprised 1.5-3.3% of the total makeup of Cambodia soil samples and 11.7-20.0% of Jordan soils. The majority of the soils were comprised of 45 other ‘major’ and ‘trace’ elements. ‘Trace’ elements are typically found at extremely low concentrations; instead of percent, typical units are parts per million, or \(\mu g\) g\(^{-1}\). Three elements (Ba, Cr, Sr) were analyzed twice, via the two different methods (p. 136).

As is typical for soils, the most common element was silica, or SiO\(_2\); SiO\(_2\) is found in quartz, which is an important component of sand. The median SiO\(_2\) concentration was 60% in Cambodia soils, slightly greater than the median concentration of 47% for Jordan soils. The next 3 most common ‘components’ of the soils were ‘loss-on-ignition’ (LOI, obtained by ashing soils at 1000\(^\circ\)C for 1 hr), aluminum (Al\(_2\)O\(_3\)), and iron (Fe\(_2\)O\(_3\)). For Cambodia | Jordan soils, median values of these constituents were 16.5 | 20.0, 12.1 | 10.0, and 6.1 | 5.3 %, respectively. So taken together, SiO\(_2\)+Al\(_2\)O\(_3\)+Fe\(_2\)O\(_3\)+LOI accounted for 82-94% of the soils.

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**Figure 10** depicts the comparison of the average sums of three ‘major’ elements (SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$) between Cambodia and Jordan, as well as two additional ‘major’ elements (CaO, MgO). The greater proportion of SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$ is consistent with the higher clay content, while the greater proportion of the two principal ‘base’ cations, Ca and Mg, is consistent with dust-influenced, arid ecosystems.

**Figure 10.** Comparison of the average sums of different ‘major’ elements between Cambodia and Jordan soil samples

**Figure 11** shows a comparison of loss-on-ignition data from two procedures. These data would imply that LOI as quantified in the JMU Soils Lab underestimates SOM for Jordan soils relative to Cambodia soils with the same %LOI. For example, a JMU LOI value of 4% could be associated with a Cambodia ALSC LOI value of 10%, but a Jordan ALSC LOI value of 18% (see dashed vertical line).

**Figure 11.** A comparison of loss-on-ignition data from two procedures.
Figure 12 exhibits the comparison of explanatory power of LOI to predict soil carbon. To check this whether JMU LOI underestimated soil carbon relative to ALSC LOI, we regressed JMU LOI against soil carbon and found that JMU LOI explained 77-89% of the variance in soil carbon, as determined at the University of Nebraska, a slightly greater proportion of the variance than when ALSC LOI was regressed against soil carbon (67-79%).

![Graph showing the comparison of LOI explanatory power to predict soil carbon.](image)

**Figure 12.** Comparison of LOI explanatory power to predict soil carbon.
The graph in Figure 13 captures the somewhat unexpected result that Jordan soils contained slightly more\textsuperscript{52} soil carbon than Cambodia soils. Although we estimated that Cambodia soils contained more soil organic matter than Jordan soils based on our loss on ignition results, the combustion of soils at high temperatures can also release ‘waters of hydration’—or crystalline water held tightly within clays, so tightly that it is not ‘baked off’ even at temperatures greater than 100°C.

A less surprising result is that while the soil carbon values are comparable, soil nitrogen values were not. This is illustrated in the comparison of carbon-to-nitrogen ratios (C:N), which shows that the Jordan C:N were much higher than the Cambodia C:N. In fact, nitrogen in Jordan soils averaged 0.17%, about 36% less than Cambodia soils (0.27%).

![Graph showing soil carbon and C:N ratios for Cambodia and Jordan soils.](image-url)

\textbf{Figure 13.} Soil carbon and carbon-to-nitrogen ratios of Cambodia and Jordan soils

Although it might be tempting to attribute differences in soil C:N to patterns of landmine aging, a closer inspection of the same landmines, determined in the field to either be likely to function or unlikely to function as intended, does not reveal any systematic pattern. As indicated in Table 4, both functional and non-functional PMN landmines had relatively high C:N, implying potential nitrogen limitation of soil decomposition processes. Conversely, all PMD6 landmines were deemed not functional and yet showed the greatest range in C:N.

\textsuperscript{52} (although most likely not \textit{significantly} more since 1 standard error of the mean [SE] is \textasciitilde 0.3%)
**Table 4.** Test of whether lower soil C:N might be associated with more rapid landmine aging, conducted on sample mines from Cambodia and with median Cambodia and Jordan ratios

<table>
<thead>
<tr>
<th>Soil sample</th>
<th>C:N</th>
<th>Associated mine</th>
<th>Field functionality assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6</td>
<td>14.7</td>
<td>PMD6</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C7</td>
<td>9.0</td>
<td>PMD6</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C8</td>
<td>11.3</td>
<td>PMD6</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C9</td>
<td>14.1</td>
<td>PMN</td>
<td>‘Likely functional’</td>
</tr>
<tr>
<td>C12</td>
<td>15.0</td>
<td>PMN</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C13</td>
<td>14.0</td>
<td>PMN</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C14</td>
<td>13.2</td>
<td>PMN</td>
<td>‘Likely functional’</td>
</tr>
<tr>
<td>C15</td>
<td>12.5</td>
<td>PMN</td>
<td>‘Likely functional’</td>
</tr>
<tr>
<td>C17</td>
<td>13.2</td>
<td>PMN</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>Median Cambodia</td>
<td>13.2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Median Jordan</td>
<td>22.8</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

At the other end of the concentration spectrum, several elements were present at levels below the instrument detection limit (DL): silver (Ag) was only detected in 1 of 17 Cambodia soils and 1 of 11 Jordan soils (DL: 1 μg g\(^{-1}\)); molybdenum was not detected in any Cambodia soils (DL: 2 μg g\(^{-1}\)), but was found in all Jordan soils (range 2-3 μg g\(^{-1}\)); thallium was detected in 9 of 17 Cambodia samples (DL: 0.6 μg g\(^{-1}\); range 1.7-3.2 μg g\(^{-1}\)), but none of the Jordan samples.

Of potentially greater interest for the purposes of quantifying landmine aging are landmine constituents such as tin (Sn), particularly since Sn values showed some of the greatest ranges across all 50 constituents. For example, as **Table 5** illustrates, three Cambodia samples (C7, C12, and C17) contained >20 μg Sn g\(^{-1}\), although 7 other Cambodia samples contained only 2 μg Sn g\(^{-1}\).

**Table 5.** Test of whether soil tin concentrations might provide field indication of landmine aging for Cambodia samples, with median Cambodia and Jordan concentrations

<table>
<thead>
<tr>
<th>Soil sample</th>
<th>Tin concentration (μg Sn g(^{-1}))</th>
<th>Associated mine</th>
<th>Field functionality assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6</td>
<td>4</td>
<td>PMD6</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C7</td>
<td>23</td>
<td>PMD6</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C8</td>
<td>7</td>
<td>PMD6</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C9</td>
<td>3</td>
<td>PMN</td>
<td>‘Likely functional’</td>
</tr>
<tr>
<td>C12</td>
<td>34</td>
<td>PMN</td>
<td>‘Likely functional’</td>
</tr>
<tr>
<td>C13</td>
<td>14</td>
<td>PMN</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>C14</td>
<td>5</td>
<td>PMN</td>
<td>‘Likely functional’</td>
</tr>
<tr>
<td>C15</td>
<td>5</td>
<td>PMN</td>
<td>‘Likely functional’</td>
</tr>
<tr>
<td>C17</td>
<td>39</td>
<td>PMN</td>
<td>‘Not likely functional’</td>
</tr>
<tr>
<td>Median Cambodia</td>
<td>3.5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Median Jordan</td>
<td>2.0</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Figure 14 presents the Table 5 calculations of tin concentration in Cambodia samples graphically for another way of understanding the data. In a comparison of soils collected with PMN (n=6) and PMD-6 (n=3) landmines in Cambodia, average (±1SE) tin concentrations in the vicinity of landmines assessed as ‘not capable of functioning as intended’ were 20±6 μg Sn g⁻¹, whereas average tin concentrations next to ‘likely to function as intended’ landmines were 4±1 μg Sn g⁻¹. These results suggest that corrosion of landmines could be associated with ‘leakage’ of Sn into the surrounding soil. Tin, therefore, might be useful in chemically ‘fingerprinting’ aging landmines since one consequence of the corrosion of landmines will be the release into the surrounding soil of ‘weathering products’ such as tin.

It is important to note, however, that the relatively small sample size precludes broader generalizations. First, nearly the same range of values (4-23 μg Sn g⁻¹) was observed in soils collected adjacent to two non-functional PMD6 landmines. Second, Jordan samples J7 and J8 were collected adjacent to ‘functional’ and ‘non-functional’ M14 landmines, respectively, but the soils contained identical concentrations of tin: 2 μg Sn g⁻¹.

This finding illustrates well an important outcome of this research. The Jordan results fall short of being an adequate test of the tin-leakage finding because even if some tin leakage had been associated with corrosion of the M14 landmines, the sandier textures (only ~31% clay) of the Jordan soils (versus ~60% clay for Cambodia soils) could have resulted in greater leaching of any ‘leaked’ tin. Future work should target material properties associated with landmines distributed across gradients of potential leaching. The most accessible of these gradients would be catenas, or hillslopes, where the same landmines can be found at crests (relatively dry) and at toeslopes (relatively wet).

Only one other element (barium [Ba]) showed as great a range as Sn (20) in Cambodia soils; ICP-MS values for Ba ranged between 122 and 2270 μg g⁻¹, whereas XRF values ranged
between 0.01 and 0.24%. Similarly pronounced ranges were not encountered in Jordan soils: phosphorus as P$_2$O$_5$ ranged between 0.17 and 0.57%, and lead (Pb) ranged from 14 to 53 μg g$^{-1}$.

One rock sample from Jordan was analyzed to gain some insights into the extent of chemical weathering observed in Jordan soils, using standard mass balance approaches:\textsuperscript{53,54}

$$\tau_{\text{Si}} = \frac{((\text{Soil Si} \times \text{rock Zr})}{(\text{soil Zr} \times \text{rock Si})) - 1)*100$$

If we assume zirconium (Zr) is an immobile element in these soils, the ratio of median Si in soil to the Si in the rock, divided by the ratio of median Zr in soil to the Zr in the rock yields the not-too-surprising finding that the Jordan soils have lost 98% of the Si present in the parent material rock. This loss is extremely difficult to reconcile with the relatively sandy textures (and therefore, quartz- and SiO$_2$-rich content of the soils).

Furthermore, applying the same calculations to Ca and Na produces losses of 15 and 72 percent, respectively. It is difficult to imagine how losses of these cations, which are important components of ocean water—and a reason the oceans are salty, could be smaller than losses of Si, and in the case of Ca, nearly 7 times smaller. These data point to an increasingly well-recognized phenomenon: arid soils are more frequently born of aeolian parent material (dust) than the underlying rock.

In contrast with the Cambodia soils, where we observed some large differences in elemental chemistry between samples, most Jordan soils were quite comparable. There were, however, pronounced differences between the single rock sample that was analyzed and the median Jordan soils. Nineteen elements showed order-of-magnitude or greater differences between the median soil concentration and the single rock sample: Ce, Co, Eu, Ga, Hf, Nb, Nd, Pr, Rb, Sm, Ta, Th, Zr, and among the ‘major’ elements, Al, Ca, Mg, K, Ti, and LOI.

**IMPLICATIONS AND CHALLENGES OF CURRENT RESEARCH**

This study has highlighted the soil properties associated with a number of different landmines collected from Cambodia and Jordan since 2009. Unfortunately, because no comparisons of the same landmine deployed for different intervals of time in the same soil were available, nor the same landmine deployed for identical intervals of time across different soils, our initial investigation of the soil properties most likely to predict the trajectory of ‘landmine aging’ has failed to zero in on a single ‘most promising’ soil property meriting further study.


As Figure 15 indicates, the research team’s field assessments of landmine condition and likelihood of functioning as intended generally tracked the vulnerability index values developed during this phase of the Aging Study by the research team. This comparison suggests field assessments may provide a robust means of categorizing landmine aging, although much greater resolution of vulnerability x environmental interactions—as these interactions affect landmine aging and degradation—might be possible through sampling strategies that maximize a gradient approach to landmine aging.

At the Fall 2010 Geological Society of America Annual Meeting, preliminary results from this project were presented in a poster comprised of 4 sections, each headlined by a question:

Q1. What is landmine aging?
Q2. What is a pedological approach to landmine aging?
Q3. What soil property best explains landmine vulnerability to aging?
Q4. So what?

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The poster developed for the Geological Society of America Annual Meeting is reproduced in Figure 16. This poster highlighted primary work on elemental concentrations for Cambodia soil in order to focus on one approach to indexing the variability within Cambodia soils and between Cambodia and Jordan soils.

Figure 16. Poster submission related to report research and preliminary findings for Fall 2010 Geological Society of America Annual Meeting, presented by T. Hartshorn, PhD.

In order to better understand the question asked in poster presentation, “What soil property best explains landmine vulnerability to aging?”, the research team calculated the explanatory power of different soil properties, with respect to vulnerability index values (Table 6). The outcome of this analysis indicates that the soil property best explaining landmine vulnerability depends on whether the landmines are considered by region (Cambodia, Jordan) or together. For all landmines together, the carbon-to-nitrogen ratio (C:N) explained 51 percent of the variance in vulnerability index values (highlighted in green), while silt explained 44 percent of the variance.

The Denver poster reception was generally enthusiastic. One individual from the New Mexico Institute of Technology noted that the soil properties that had been analyzed (for the poster: pH, EC, texture, soil organic matter, carbon, and nitrogen) were ‘agricultural’ and that what would probably drive landmine aging would be water. The research team agreed and noted that we cannot measure the moisture content of the soil over the ‘lifetimes’ of deployed landmines, and so we are attempting to index not only soil moisture, but acidity, with soil properties such as soil organic matter, which is comprised mostly of the elements carbon and nitrogen, as well as texture. Together, these are the two soil properties that are best used for indexing soil moisture.
Table 6. Summary of explanatory power of different soil properties with respect to vulnerability index values. Values can range from 0 to 1, where 1 would mean that all of the variance in vulnerability index values is explained by that specific soil property.

<table>
<thead>
<tr>
<th>Property</th>
<th>Cambodia</th>
<th>Jordan</th>
<th>Both</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>0.07</td>
<td>0.04</td>
<td>0.35</td>
</tr>
<tr>
<td>EC</td>
<td>0.28</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>%sand</td>
<td>0.27</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>%clay</td>
<td>0.36</td>
<td>0.00</td>
<td>0.25</td>
</tr>
<tr>
<td>%silt</td>
<td>0.00</td>
<td>0.21</td>
<td>0.44</td>
</tr>
<tr>
<td>%SOM</td>
<td>0.05</td>
<td>0.11</td>
<td>0.23</td>
</tr>
<tr>
<td>%Carbon</td>
<td>0.03</td>
<td>0.17</td>
<td>0.00</td>
</tr>
<tr>
<td>%Nitrogen</td>
<td>0.01</td>
<td>0.15</td>
<td>0.21</td>
</tr>
<tr>
<td>C:N</td>
<td>0.26</td>
<td>0.14</td>
<td>0.51</td>
</tr>
</tbody>
</table>

The research team also presented a poster at the SERDP/ESTCP Annual Symposium\textsuperscript{56} where the research project’s major and trace element work was expanded upon (see Figure 17).

Commentary from attendees of the 2010 SERDP/ETSCP Symposium highlighted two future considerations. The first is to investigate the potential for characterizing landmine components and soils associated with Israeli minefields; these could profitably be compared with Jordan samples, with potentially similar climates and soils. The second is to investigate other southeast Asian minefields, where landmine emplacement might reflect different region-specific conflicts, thus enabling ‘time-stamping’ of landmine aging trajectories, if the same landmines can be characterized (e.g., PMN). For example, conflicts in Cambodia, Laos and Vietnam have led to the creation of minefields that may hold the same landmine types, but laid at different times—all with potentially comparable climates and soils. Characterization of PMN landmines that were emplaced in similar soils during different time periods might profitably help clarify the trajectories of landmine aging.

One major outcome of initial soils analysis, which the Denver poster in particular clarified, is the recognition that the approach undertaken during this phase of Aging Study research was unusually constrained with respect to landmines and aging processes. Just as parent rock weathering extents will vary as a function of the various soil-forming factors and the processes, so too will landmines be affected by environmental aging processes.

Unfortunately, however, due to real-world field collection constraints faced during the current phase of research, this pilot and, arguably, proof-of-concept study did not afford access to identical mines with deployment dates ranging across decades (a soil chronosequence approach, where the one factor that is experimentally manipulated is duration of soil-forming factors or processes).

Rather, this study relied on 18 soil samples from Cambodia and 15 soil samples from Jordan. All mines that were characterized were specific to the country of origin, so even though soil properties differed between Cambodia and Jordan, we were unable to assess functionality of the same landmine deployed into two broadly different soil types.

The scope of current research on aging effects on landmines was limited, and ultimately the research team faced the problem of not being able to conduct research techniques that allowed a comparison of identical mines deployed for identical durations into:

- soils representing a toposequence (same macroclimate, same biota, same parent rock, but different parts of a hillslope or catena: crest, shoulder, sideslope, footslope, toeslope);
- soils representing a climosequence (same biota, same rock, same catena position, but different macroclimate zones); or
- soils representing a lithosequence (same macroclimate, same biota, same catena position, but different parent rock).

Although the research team was able to analyze and characterize soil samples from Cambodia and Jordan, and hypothesize about effects of environmental characteristics on the sample mines, the small number of same mine types did not allow comparative techniques that might have been able to isolate critical factors affecting landmines within an environment with scientific confidence.
CONCLUSIONS AND RECOMMENDATIONS

- **Greater number of matched soil/landmine pairs (functioning and not functioning).** This project has benefited from a substantial investment in planning, site visits to Cambodia and Jordan, landmine part and soil characterization, analyses, and report preparation. In fact, this study benefited from the collection of 6 PMN landmine/soil pairs, half of which were deemed ‘functional’ and the other half ‘not functional.’ This enabled us to compare soil properties associated with examples of the same landmine deemed to represent two parts of a ‘functionality continuum.’

However, a comparable future investment might yield clearer results if country- or region-specific landmines such as the PMN or M14 can be targeted, with the goal of characterizing more landmine/soil pairs, even if these samples represent a smaller overall sampling of all possible landmine/soil pairs. As one specific example, if more PMN landmines are collected from a greater variety of environmental settings (top of a hillslope, middle of a hillslope, bottom of a hillslope), greater insights into the role of soils in landmine aging may be possible.

Additionally, more matched landmine/soil pairs in future research are recommended, including both functional and likely-not-functional samples. As an example of the challenge faced in the current research phase related to this pairing, the M19 from Jordan was deemed functional, and was associated with soils with a very high carbon-to-nitrogen (C:N) ratio (33.3). This high C:N would suggest that microbial activity might be more limited, and therefore less likely to produce acidity capable of corroding this landmine, but in the absence of other M19 landmine/soil pairs deemed ‘not functional’ this conclusion would be tenuous at best.

- **Retaining of soils for future research.** Per our US Department of Agriculture foreign soil permit, we are only allowed to retain foreign soils for a period of <1 year. The JMU Soils Lab research team have begun the process of requesting an official extension, so that as our findings are disseminated (2 posters at national meetings in 2010, and a peer-reviewed manuscript expected to be in press in 2011), some of the remaining sample material will be available to interested parties for follow-on analyses.

- **Strategic expansion of locations for comparative advantage.** Commentary from preliminary presentation of soils analysis results at two conference events highlights feedback from peers that has indicated future areas of research related to new locations in order to maximize understanding of current sample analysis. One recommendation is to investigate the potential for characterizing landmine components and soils associated with minefields similar to our current research (e.g., Israeli samples, which could profitably be compared with Jordan samples, due to potentially similar climates and soils). The second is to investigate other southeast Asian minefields, where landmine emplacement might reflect different region-specific conflicts, thus enabling ‘time-stamping’ of landmine aging trajectories, if the same landmines can be characterized (e.g., PMN). For example, conflicts in Cambodia, Laos, and Vietnam have led to the creation of minefields that may hold the same landmine types, but laid at different times—all with potentially comparable climates.
and soils. Characterization of PMN landmines that were emplaced in similar soils during different time periods might profitably help clarify the trajectories of landmine aging.

- **Increased, strategic collection of global field data.** While the research team had some success in acquiring shapefiles of mine clearance data, a much greater level of cooperation would help leverage and extrapolate our current results. For example, records of where potential ‘functional’ vs. ‘non-functional’ landmines were found can be cross-referenced with georeferenced geochemical databases, as well as indices of degradation vulnerability such as that developed by Colin King, to derive estimates of landmine aging trajectories.

In order to make the Aging Study research findings relevant to non-governmental as well as governmental organizations, it is critical to collect whatever available data there is including: where (precisely) mines have been cleared from and where they remain to be cleared from; the density of landmines encountered; some assessment of their presumed functionality (="age"); some indication of the timing of deployment of the landmines; landmine specifics (e.g., mine type, so that we can cross-index its initial vulnerability index value); and finally any environmental characteristics.

- The research team acknowledges these data are difficult to obtain under the most ideal of circumstances, but believe greater coordination with clearance organizations will greatly facilitate the collection of data that can assist in the determination of environmental conditions associated with landmines defined to be of a certain functionality. This is evidenced in a proposed field form developed by the larger research team during this phase of research (found in *Annex K*).

- **Aging Landmines Data Repository.** Mine clearance efforts represent a tremendous investment of financial and human resources; part of the return on this investment is a stream of very rich data. Unfortunately much of this return on the initial and continuing (mine risk education, for example) investment is never realized because there is no good repository for these streams of data, nor are rudimentary quality control measures in place for filtering those streams of data. As mine clearance funding evaporates, much greater returns on (increasingly smaller) investments in mine clearance could be achieved through a very modest investment in further exploration of the ways and rates at which landmines age and cease to function as intended.

If science-based allocation of scarce mine clearance resources (human, financial) is a local, regional, national, or international priority, this goal can only be achieved at minimum expense through a systematic effort to capture and make available data. Until these data are broadly available for meta-analyses by third parties, mine clearance progress will be limited to very small-scale studies such as this one to help prioritize mine clearance strategies. With greater data, patterns and extrapolation of landmine aging trends can be more confidently and accurately found and used to advantage in humanitarian mine action.