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Predictive Environmental Health Risk Assessment for Military Operations: From Historical Experience to Science-Informed Decision-Making

David R. Speidel[1]
Employment State of Missouri Department of Education. Retired Foreign Agricultural Service, Washington DC, USA.

Dmitry Nikolaenko
Editor-in-Chief, Pollution and Diseases

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Abstract

Military operations may create environmental exposure pathways with consequences that persist long after immediate tactical objectives have been achieved. Hazardous chemicals, petroleum products, contaminated soils and water, damaged industrial infrastructure, waste, combustion products, and other military-related environmental hazards can affect civilian populations, military personnel, ecosystems, and food systems for decades. Although environmental toxicology and exposure science have substantially improved understanding of these risks, long-term environmental and public-health consequences remain insufficiently integrated into military planning and operational decision-making.

The military use of tactical herbicides during the Vietnam War provides one of the best-documented historical examples of this institutional and scientific challenge. Between 1961 and 1971, extensive areas of southern Vietnam were sprayed with herbicide formulations containing 2,4,5-T, some of which were contaminated with 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). Subsequent research has documented the persistence of TCDD in soils, sediments, aquatic environments, and food chains. Reported geographical differences in congenital heart disease and other adverse health outcomes also warrant continued investigation of possible associations with historical environmental exposure, while recognizing the methodological complexity of establishing causality in population-based studies.

The significance of the Vietnam experience extends beyond retrospective documentation of contamination. It illustrates a broader institutional problem: scientific

[1] Corresponding author drspeidel@att.net

observations, technical warnings, and environmental-health evidence may exist without becoming an effective component of operational decision-making. Similar lessons can be drawn from the contemporary professional field and published observations concerning contaminated military sites, petroleum and chemical exposure, industrial disposal practices, and operational planning in Bosnia-Herzegovina, Iraq, Afghanistan, Uzbekistan, and the United States (U.S).

This paper proposes an initial framework for Predictive Environmental Health Risk Assessment in military operations. The framework is intended to complement existing operational risk-management procedures by incorporating environmental toxicology, exposure pathways, environmental epidemiology, ecosystem persistence, bioethics, local environmental and cultural knowledge, institutional information flow, and long-term monitoring into military education and command planning.

The objective is not to eliminate uncertainty from military decision-making. Rather, it is to improve professional judgement under uncertainty by ensuring that relevant environmental and public-health evidence is identified, evaluated, communicated, and considered before operational decisions are implemented. Predictive Environmental Health Risk Assessment may therefore provide a practical foundation for reducing future environmental contamination, chronic disease, disability, and long-term human suffering associated with military operations.

Keywords: Predictive Environmental Health Risk Assessment; military operations; science-informed decision-making; environmental toxicology; exposure pathways; TCDD; environmental epidemiology; operational risk assessment; military education; bioethics.

Key Points

1. Existing military risk-management procedures primarily address immediate operational hazards and may insufficiently represent delayed exposure pathways, persistent ecosystem contamination, and chronic public-health consequences.
2. This papers and the Journal Pollution and Disease's research methodology is outlined.
3. Historical cases such as the military use of herbicides in Vietnam provide an empirical basis for developing predictive approaches to environmental-health risk assessment.
4. The professional field observations provide a contemporary assessment that reinforces the historical environmental health concerns are still a hazard requiring planning and primitive actions to mitigate.
5. Predictive Environmental Health Risk Assessment should integrate environmental toxicology, exposure science, epidemiology, ecosystem monitoring, bioethics, institutional communication, and local environmental knowledge.
6. Scientific evidence becomes operationally useful only when institutions can identify, evaluate, communicate, and incorporate it into command decision-making.
7. The purpose of the proposed framework is not perfect prediction, but better-informed professional judgement under conditions of uncertainty.

Introduction

Science-Informed Decision-Making in Military Operations

Modern military operations are conducted in environments where tactical objectives, human health, and environmental security are closely interconnected. Commanders routinely assess risks to personnel, equipment, logistics, mobility, intelligence, and mission accomplishment. Environmental and public-health risks, however, may receive less systematic attention, particularly when their consequences are delayed, geographically dispersed, or expected to emerge only after an operation has ended.

This separation of immediate risk from tactical-operational decisions and the convenience of not considering long term environmental health risk is increasingly difficult to justify. The consequence of future harm to much larger number of service members, than being risked in the operation, to current civilians, and future civilian populations makes such a failure for convenience, to plan for the future consequence, a negligent act.

Military decisions involving hazardous chemicals, fuels, waste, damaged industrial infrastructure, land modification, water resources, agricultural systems, combustion products, and contaminated sites may create exposure pathways that persist for years or decades. The resulting consequences can extend beyond the operational area and affect military personnel, civilian populations, ecosystems, food systems, public-health services, and post-conflict recovery.

The central problem is not always the complete absence of scientific knowledge. In many cases, relevant observations, technical warnings, or partial evidence already exist. The more consequential institutional failure occurs when such knowledge is not identified, evaluated, communicated, and incorporated into operational decision-making. Scientific information may remain isolated within laboratories, private companies, government agencies, medical institutions, or specialized professional communities. It may be fragmented, delayed, discounted, or filtered as it moves through administrative and military hierarchies. As a result, decision-makers may act without access to the best available evidence, even when that evidence could materially alter an operational plan.

The military use of tactical herbicides during the Vietnam War provides one of the best-documented historical examples of this broader problem. Between 1961 and 1971, extensive areas of southern Vietnam were sprayed with herbicide formulations containing 2,4,5-T, some of which were contaminated with TCDD. The operational objectives included reducing vegetation that concealed opposing forces and destroying crops believed to support insurgent activity. The environmental and human consequences, however, extended far beyond those immediate tactical purposes.

Subsequent research has documented the persistence of TCDD in soils and sediments, its movement through aquatic environments and food chains, and continuing concerns regarding chronic and potentially intergenerational health effects. Studies reporting geographical differences in congenital heart disease and other adverse

health outcomes warrant continued investigation of possible associations with historical environmental exposure. At the same time, the complexity of environmental epidemiology requires caution: geographical correspondence and statistical disparity do not, by themselves, establish causation. The scientific importance of the Vietnam case lies both in the evidence already established and in the questions that remain unresolved.

The Vietnam experience has been examined extensively from the perspectives of toxicology, environmental persistence, epidemiology, veterans' health, military history, and political responsibility. The purpose of the present paper is therefore not simply to revisit the established history of Agent Orange. Instead, the Vietnam experience is used as the principal historical case through which a broader professional and institutional question can be examined.

How can scientific knowledge about long-term environmental and human-health consequences become an effective component of military operational decision-making before potentially harmful actions are undertaken?

This question remains relevant to contemporary armed forces. Military personnel and civilian populations may be exposed to petroleum products, industrial chemicals, contaminated soils and water, damaged infrastructure, munitions residues, combustion products, biological hazards, and other environmental threats. Some hazards are created directly by military activity. Others are inherited from previously contaminated military, industrial, or agricultural sites. In both situations, the consequences may include acute illness, chronic disease, disability, loss of operational effectiveness, ecological degradation, delayed civilian recovery, and diminished public trust.

Military decisions necessarily occur under conditions of urgency, uncertainty, competing objectives, and incomplete information. It would therefore be unrealistic to suggest that every environmental consequence can be predicted or prevented. The appropriate objective is not perfect foresight. It is the creation of institutional processes that improve the probability of recognizing serious hazards before they produce irreversible harm.

This paper uses the term Predictive Environmental Health Risk Assessment to describe an emerging approach for identifying, evaluating, and communicating the possible long-term environmental and public-health consequences of military activities before operational decisions are implemented. The approach is not intended to replace established military risk-management systems. Rather, it is intended to extend them by incorporating forms of evidence that may be insufficiently represented in assessments focused primarily on immediate probability, severity, and mission impact.

Predictive Environmental Health Risk Assessment should therefore consider not only a tool to mitigate an immediate hazardous event but also to analyze the tactical sequence through which long-term harm may develop when the decision to employ weapons are made:

Tactical sequence hazardous activity or material → the environmental release into → degree of persistence and means of transport → mechanism of human or

ecological exposure the delayed health outcomes → impact of long-term social and operational consequences.

The predictive task is not to calculate every future outcome with certainty. It is to identify plausible exposure pathways, examine the persistence and mobility of hazardous substances, recognize sensitive populations and ecosystems, evaluate the quality and limits of available evidence, and ensure that potentially consequential uncertainty becomes visible to commanders.

This requires more than communication in the narrow sense. Reports may be written and transmitted without becoming part of the actual decision process. What is needed is the institutional integration of scientific knowledge into military planning. This includes clearly defined responsibilities, structured environmental-health assessment, reliable reporting channels, access to relevant expertise, procedures for challenging incomplete assumptions, and command processes that require long-term environmental and public-health consequences to be considered alongside other operational risks.

Leadership education is central to this process. Officers are trained to evaluate threats, compare courses of action, balance probability and severity, and make decisions under pressure. These professional skills provide a foundation for environmental-health risk assessment. Their effectiveness, however, depends on whether leaders are trained to recognize environmental hazards, ask appropriate scientific questions, identify missing information, distinguish evidence from assumption, and determine when specialist expertise is required.

Bioethics can strengthen this professional preparation by helping military leaders consider how operational decisions may affect individuals and communities that do not participate directly in the decision process. Its purpose is not to replace military judgement with abstract moral reasoning. Rather, it can help ensure that foreseeable long-term consequences for civilians, military personnel, future generations, and ecosystems are recognized as legitimate components of professional risk assessment.

Local environmental and cultural knowledge is equally important. Military operations take place within ecological, agricultural, social, economic, and political systems that may be unfamiliar to deployed personnel. Seasonal hydrology, local food chains, previous industrial activity, land-use practices, community behavior, institutional incentives, and political relationships any of these may influence the existence of a hazard. The understanding of the information received due to multiple factors as unfamiliar cultures, complex hazardous materials and environments, makes accurate decisions a challenge.

Scientific evidence cannot be separated entirely from the institutions and human relationships through which it is collected, interpreted, and acted upon. Effective assessment must therefore include both measurable environmental indicators and the organizational conditions that determine whether those indicators are disclosed, trusted, understood, and transmitted through the chain of command.

The examples described in this paper are observations made in and studies from Vietnam, Bosnia-Herzegovina, Iraq, Afghanistan, Uzbekistan, and herbicide-manufacturing sites in the United States. These cases differ substantially in geography, history, and operational setting, but they reveal a recurring pattern: environmental evidence may be observable or available while remaining outside the effective decision process.

This paper examines these cases not as equivalent environmental events, nor as a basis for assigning retrospective blame, but as sources of professional learning. Their relevance lies in the institutional questions they raise:

- What information was available?
- What information was missing?
- Who had the capacity to recognize the hazard?
- Through what channel could the evidence reach decision-makers?
- What organizational or cultural factors influenced its interpretation?
- Which alternative actions were possible?
- What monitoring would have been necessary to identify delayed consequences?

The paper has four objectives:

1. to demonstrate how failures to integrate available scientific knowledge can contribute to long-term environmental and human-health consequences;
2. to identify institutional, organizational, and cultural barriers that may prevent relevant evidence from reaching military and civilian decision-makers;
3. to propose an initial framework for Predictive Environmental Health Risk Assessment that complements existing military risk-management procedures;
4. to identify priorities for military education, scientific collaboration, reporting, monitoring, and future methodological development.

The article first examines the Vietnam herbicide programme as a historical case of long-term environmental persistence and incomplete integration of scientific knowledge. It then considers contemporary operational and industrial cases to identify recurring problems in hazard recognition, information flow, and risk mitigation. Finally, it proposes the initial components of Predictive Environmental Health Risk Assessment and discusses how they may be incorporated into military education and operational planning.

The underlying argument is that environmental and public-health protection should not be treated as an external limitation on military effectiveness. When properly integrated into planning, environmental science can improve force protection, operational resilience, resource management, civilian recovery, institutional legitimacy, and long-term mission outcomes.

The objective is not to remove uncertainty from military decision-making. It is to support *better-informed professional judgement under uncertainty*.

2. Approach and Sources of Evidence

Position of the Journal Pollution and Diseases

This article is intended, in part, as a programmatic paper for the journal Pollution and Diseases. It reflects one of the journal's principal directions of development.

The journal was established at the end of 2025. Its most significant achievement to date has been the organization of the international conference on Military Pollution of Soil and Freshwater Resources (15–17 October 2026, Prague). Preparation for the conference has proceeded across several complementary research directions, including:

- Philosophical and methodological studies. Military pollution is regarded as a highly complex object of scientific inquiry. Current work seeks to develop a new scientific approach to its investigation. Several publications examine, from different theoretical perspectives, how this phenomenon can be studied in the most rigorous and methodologically appropriate manner (1-4).
- The role of the expert community in the preparation for war and its direct involvement in military activities (5). Research in this area is ongoing. It addresses a topic that remains highly unpopular within the scientific community: How can a scientist become a war criminal?
- Studies of the Vietnam War from the perspective of environmental contamination and its long-term consequences (6). The Vietnam experience is considered not only as a historical case but also as a foundation for developing new scientific research directions.
- Military pollution and public health. This is an extensive field encompassing many different aspects (7-9). The subject is examined from substantially different scientific perspectives.
- Soil contamination as a long-term process (10,11). This form of pollution includes numerous environmental, ecological, and societal dimensions that require systematic investigation.
- Identification and investigation of new forms of military pollution (12,13).
- Engineering structures and their unexpected transformation into infrastructure that contributes to the contamination of territories and aquatic environments indirectly associated with military production (14,15). This research identifies an entirely new dimension of military-related environmental contamination that has received little or no previous scholarly attention.
- Military conflicts, transformations of settlement systems, and their long-term consequences (16). This represents a broad field of research with numerous empirical cases requiring further investigation.
- Indirect effects of military production on the natural environment and living organisms. Particular attention has been given to changes in the populations of New Zealand dolphins (17-21).

These studies represent only the beginning of the work carried out by the expert group associated with the journal Pollution and Diseases. By the end of 2026, the

number of publications is expected to increase substantially, largely as a result of the scientific activities associated with the conference.

The distinguishing feature of the journal is not merely the number or breadth of topics related to military pollution. More fundamentally, the journal approaches military pollution as a long-term process. Its research is directed toward identifying the morphology of that process. We are not satisfied with a cognitive approach that treats military pollution as a collection of isolated and unrelated unique cases. Instead, we seek to elevate these studies to the level of morphological analysis, thereby revealing the common processes that underlie individual cases.

2.1 Conceptual approach

This paper adopts a case-based conceptual and policy analysis rather than a systematic review or quantitative modelling study. Its objective is not to establish new epidemiological associations or to reconstruct the complete environmental history of the Vietnam War. Instead, it seeks to identify general principles that may strengthen future military decision-making when environmental and public-health risks are involved.

The central premise of the paper is that well-documented historical environmental events can serve as professional learning systems. Historical military operations provide opportunities to examine not only environmental consequences themselves, but also the institutional processes through which scientific knowledge was—or was not—incorporated into operational planning. The objective is therefore prospective rather than retrospective. Historical evidence is used to inform future military education, environmental governance, and operational risk assessment.

Accordingly, Vietnam is treated as the principal historical case study through which broader institutional questions can be examined. The intention is not to generalize automatically from one conflict to all future military operations, but rather to identify recurring patterns that may have wider relevance for environmental health risk governance.

2.2 Sources of evidence

The analysis integrates several complementary forms of evidence.

First, the paper draws upon published scientific literature concerning the environmental persistence of TCDD, environmental toxicology, exposure pathways, environmental epidemiology, congenital heart disease, military herbicide operations, environmental contamination, and long-term ecosystem impacts. These studies provide the scientific foundation for understanding the environmental behavior of hazardous chemicals and their possible long-term consequences.

Second, historical documentation concerning the military use of herbicides during the Vietnam War is examined to illustrate how operational objectives, available scientific knowledge, institutional communication, and subsequent environmental consequences became interconnected.

Third, the paper incorporates, in section 4.1, documented professional field observations from contemporary military and civilian service in Bosnia-Herzegovina, Iraq, Afghanistan, Uzbekistan, and the United States. These observations are not presented as formal scientific case studies or quantitative datasets. Rather, they are used to illustrate institutional processes through which environmental information becomes available, communicated, interpreted, or overlooked during military operations.

Fourth, the paper has added at the end, in section interview with Lieutenant General James L. Terry (Ret.). This interview examines the operational feasibility and institutional requirements of integrating environmental health information into miliary planning. This professional testimony and institutional evidence provide one, singular viewpoint by a senior officer, is an important sociological science observation rather than as a quantitative dataset. Necessary for effective transfer of knowledge in the predictive environmental risk assessment framework.

Together, these complementary sources provide the basis for examining how scientific evidence can contribute more effectively to military operational planning.

Framework evidence source: NATO. Joint NATO Doctrine for Environmental Protection during NATO-led Military Activities / STANAG 7141.

NATO. Climate Change and Security Impact Assessment.

2.3 Analytical framework methodology

The analytical framework proceeds through four successive stages.

The first stage examines historical evidence describing environmental contamination and long-term human-health consequences associated with military activities.

The second stage identifies institutional factors influencing whether relevant scientific evidence did or become available to decision-makers during operational planning.

The third stage compares historical and contemporary examples in order to identify recurring patterns in environmental risk recognition, institutional communication, organizational learning, and professional judgement.

The fourth stage proposes an initial framework for Predictive Environmental Health Risk Assessment, intended to strengthen future military planning by integrating environmental science into operational decision-making before potentially hazardous actions are undertaken.

The framework should therefore be understood as an initial conceptual contribution rather than a completed operational methodology. Its purpose is to stimulate further interdisciplinary development involving environmental scientists, toxicologists, epidemiologists, military educators, operational planners, risk analysts, policy advisors, and public-health specialists.

2.4 Predictive Environmental Health Risk Assessment

Within this paper, Predictive Environmental Health Risk Assessment is defined as the systematic identification, evaluation, communication, and incorporation of

scientific evidence concerning potential long-term environmental and public-health consequences before military operational decisions are implemented.

The proposed approach extends conventional operational risk assessment by considering environmental processes that may continue long after immediate military objectives have been achieved. These include environmental persistence, contaminant transport, ecological exposure pathways, food-chain transfer, delayed human-health outcomes, ecosystem recovery, institutional learning, and post-conflict environmental resilience.

Unlike retrospective environmental assessment, which evaluates consequences after military operations have concluded, Predictive Environmental Health Risk Assessment seeks to inform decisions before environmental damage occurs.

Its objective is therefore not prediction in the deterministic sense. Rather, it aims to improve the quality of professional judgement subject to uncertainty due to multiple factors as unfamiliar cultures, complex hazardous materials and environments.by ensuring that commanders have timely access to the best available environmental and public-health evidence during operational planning.

2.5 Scope and limitations

The present paper represents an initial conceptual contribution rather than a validated operational model.

The proposed framework has not yet been tested through prospective operational implementation and should therefore be regarded as a foundation for further methodological development.

Future research should examine the practical integration of Predictive Environmental Health Risk Assessment into existing military planning procedures, professional military education, environmental intelligence, operational doctrine, and post-conflict environmental monitoring.

Additional comparative studies involving other military conflicts, humanitarian operations, industrial accidents, and environmental disasters may further refine the framework and identify opportunities for standardization across military organizations.

3. Vietnam as Evidence for Predictive Environmental Health Risk Assessment

CASE STUDY VIETNAM

Dioxin contamination of soils and sediments in southern Vietnam is a continuing legacy of the Vietnam War (1961-1971) (22-24). One third of the country, South Vietnam, reportedly was sprayed with dioxin laced Agents Orange, Purple, Pink and Green, as well as arsenic based Blue. Some areas were repeatedly sprayed as much as eight times (22). Residues of dioxin contaminated chlorinated phenoxy herbicides formulated with 2,4,5-T (2,4,5-trichlolorphenoxyacetic) acids have persisted in areas of

known high use of herbicides and concentration south of the Vietnam 17th parallel (24)

Analysis of the military reports from sixty plus years can be challenging. The table on the right highlights the intensity of the multiple spraying across the Mekong Delta, Central Highlands and around military bases from 1961-1971. It was an intensive operation. The sum of the hectares of the target area of the villages, rice fields, jungles and mangrove swamps when added up it does not match one-third of the South Vietnam 339,000,000 landmass. Where then did the analyzers come up with this assessment? Looking at the multiple spraying runs when hectares are added plus arsenic based Agent Blue is considered, then one third is conceivable. Review of graphics referenced (22) support the conclusion.j

Table 1 Spray frequency | Hectares sprayed 2, 4, 5-T herbicides

Spray frequency	Hectares sprayed 2,4,5-T herbicides
1	343,426
2	332,249
3	275,770
4	236,232
5	153,192
6	119,127
7	75,062
8	51,371
9	32,988
10	60,316
total	1,679,734

Soil samples show that TCDD has persisted in the soil and sediments of areas where herbicides were heavily used. Over time this dioxin has bioaccumulated in fish, shellfish, clams, mussels, moved up the food chain via diets, then deposited in the fatty tissues of animals and humans (22, 23). While there are limitations in the 2020 childhood congenital heart disease (CHD) prevalence rate data analyzed by Morton and Culbertson, the disparity in rates between North and South/Central Vietnam children are not by chance alone (22). The geographical childhood CHD disparities associated with geographical regions that were not sprayed and those regions heavily sprayed with TCDD contaminated herbicides during the 1961-1971 war period is striking (22).

Comparing two maps of Vietnam shows this connection between low CHD levels and no herbicide spray and high the CHD levels discovered in the 2022 study and the published 2011 map of spray lines shown by U.S. Army 1961-1971 herbicide spray missions. North Vietnam Lang Son Province CHD levels found were 2.5/1000 CHD level compared to the heavy sprayed zones in the Central Mountains with 10.9/1000 CHD and the Mekong River Delta's 9.6/1000 CHD, another hard fought region (22).

The decision, by President Kennedy, to use the new tactical method to clear the insurgent's jungle cover was made after only two tests in 1961, the second test, selected

by South Vietnam President Ngô Đình Diệm for use on food plots of suspected insurgency sympathizers, was flawed (24). The science was not wrong, but incomplete. Businessmen and engineers, who had observed the plant accidents at MONSANTO, 1949 and BASF, 1953 (25) failed to investigate, connect the effects to the causes, and inform decision makers.

Science's value is when society decides to implement its proofs. Further, rather than leave the utility of scientific discovery to chance, science advocates must understand the impacts of the science and the cultural norms that shape the decisions of society's political, economic, and military leaders to the benefit their communities.

The scientific process is observation and measuring the physical world, tabulating the measurements, hypothesizing observation cause, verify by testing, and repeat as needed. Science is based on past scientific findings, assembly of data and testing of theories, supported by facts based on the best measurements possible. A scientist is trained and expected to deliver outcomes and conclusions based solely on his or her findings with minimal personal bias. The social science disciples have similar processes, standards, and professional expectations. The economist would say his ledgers must balance, thus, what could be more analytic? But what of human values, emotions, and cultural expectations? An entrepreneur's fear of long term financial commitment can result in too much caution and missed opportunities. When the human emotion of greed enters, it can drive business decisions in the wrong direction, misallocating resources by ignoring scientific facts and recommendations, resulting in failed enterprises and not benefiting society. Human values, emotions, and culture underlie many political and military activities.

3.1 From tactical effectiveness to long-term exposure pathways

The military herbicide programme conducted in southern Vietnam between 1961 and 1971 represents one of the most extensively documented cases in which an immediate operational objective became associated with environmental and public-health consequences extending across several decades. Tactical herbicides were used to remove vegetation that concealed opposing forces and to destroy crops believed to contribute to insurgent support. From the perspective of immediate military planning, these activities were intended to improve visibility, mobility, and operational control.

The environmental significance of the programme, however, cannot be understood solely through its tactical objectives. Some herbicide formulations containing 2,4,5-T were contaminated with TCDD, a highly persistent and toxic dioxin congener. Millions of hectares of southern Vietnam were reportedly treated with herbicides, with some locations subjected to repeated applications which intensified the levels of dioxin.

The central environmental-health issue was therefore not limited to the period of active spraying. Once introduced into environmental systems, persistent contaminants may move through a sequence of interconnected processes listed here:

application → deposition on soil and vegetation → retention in soil colloids, organic materials and sediments → redistribution through erosion and hydrology → uptake

by aquatic and terrestrial organisms → food-chain transfer → human exposure anywhere within this process

This sequence illustrates why military evaluation of hazardous substances cannot end with immediate toxicity or short-term operational effectiveness. A chemical may cease to be operationally active while remaining environmentally significant.

Published studies have documented the persistence of TCDD in soils and sediments at contaminated locations in southern Vietnam. The contaminant may accumulate in fish, shellfish, livestock, and other organisms and thereby contribute to continuing dietary exposure. These processes demonstrate that environmental systems can preserve and redistribute the consequences of military activity long after the original operation has ended.

From the perspective of Predictive Environmental Health Risk Assessment, the relevant professional question is therefore not only:

What will this material accomplish during the operation?

It is also: What environmental form will the material take after its operational use, where will it move, who may be exposed, and for how long?

3.2 Human-health evidence and the limits of causal interpretation

What is the problem?

A number of historians have proposed that United States President, John F. Kennedy's decision to use 2,4,5-T herbicides (Agents Orange, Purple, Pink & Green) contaminated with the dioxin 2,3,7,8 tetracholorodibenzo-p-dioxin (TCDD) to defoliate southern Vietnam vegetation, forests, and croplands during the Vietnam War (1961-1971) was an accident due to lack of knowledge (26) about herbicide dioxin contamination and its short term and generational health effects on adults and children as well as military personnel handling these contaminated herbicides. Dioxins are biologically and ecologically persistent chemicals, with TCDD the most toxic of all dioxins and the reference used to calculate the Toxic Equivalents (TEQs) in assessments of human health risks (22). It is tragic that President Kennedy did not know the consequences of military use of these highly toxic chemicals.

The long-term human-health consequences associated with military herbicide use remain scientifically and socially significant. Dioxins, including TCDD, are biologically active compounds associated with endocrine disruption and a range of adverse health outcomes. Their persistence in environmental medium creates the possibility of repeated or chronic exposure among populations living in contaminated areas.

One line of evidence examined in the original congenital heart manuscript concerns geographical differences in reported childhood congenital heart disease prevalence between regions of Vietnam. The analysis referenced in the article identified higher reported prevalence rates in parts of southern and central Vietnam than in northern regions and other selected Asian populations. The geographical correspondence between areas historically subjected to herbicide spraying and reported health disparities raises an important environmental epidemiological question.

This evidence must nevertheless be interpreted with appropriate caution. Geographical overlap does not establish individual exposure, dose, biological mechanism, or causation. Population-level comparisons may be influenced by differences in diagnostic access, healthcare referral patterns, screening intensity, demographic structure, maternal health, socioeconomic conditions, genetic factors, reporting systems, and other environmental exposures.

Yes, it is tragic that President Kennedy did not know the consequences of military use of these highly toxic chemicals. It is even harder to accept the human disease and suffering when the decision to use chemical warfare is deliberate. Intended or unintended, how can this happen? More importantly, how can future harm to human health be reduced or avoided under the stressful conditions of war? How can civilian and military leadership better understand the short-and long-term consequences of their battlefield decisions? How can they better learn from past mistakes, build new knowledge, and be trained to manage and mitigate potential risks to both civilian and miliary personnel? The scientific importance of these observations lies not in treating association as proof, but in recognizing when a pattern is sufficiently consequential to justify further investigation, monitoring, and precautionary action.

Predictive Environmental Health Risk Assessment must therefore distinguish among several levels of evidence based on the standard established by: World Health Organization. (2021). Human Health Risk Assessment Toolkit: Chemical Hazards (2nd.).

1. hazard evidence — whether a substance has properties capable of causing harm;
2. environmental evidence — whether the substance persists, moves, transforms, or accumulates within environmental systems;
3. exposure evidence — whether populations or ecosystems may come into contact with the substance;
4. health-association evidence — whether adverse outcomes occur more frequently under conditions compatible with exposure;
5. causal evidence — whether the relationship can be demonstrated with sufficient control of alternative explanations.

Military planners cannot normally wait for complete causal certainty before recognizing a potentially serious risk. At the same time, uncertainty must not be presented as certainty. The appropriate response is a structured assessment that makes the strength, limitations, and operational relevance of available evidence explicit.

3.3 The institutional problem: knowledge without integration

The Vietnam case is often described as an example of incomplete scientific knowledge. This description is partly correct. During the early 1960s, understanding of dioxin contamination, environmental persistence, chronic exposure, and possible intergenerational effects was considerably less developed than it is today.

However, the case also reveals a different problem. Relevant observations and warning signals may exist without being assembled into a form capable of influencing operational decisions.

Industrial accidents involving chlorinated chemical production had occurred before the large-scale military herbicide programme. Manufacturers, industrial scientists, engineers, government laboratories, medical specialists, and military organizations each possessed different pieces of potentially relevant information. The institutional challenge was not merely whether knowledge existed, but whether separate observations could be connected, evaluated, communicated, and translated into decision-relevant evidence. The case studies and examples from combat zones identifies this fragmentation of information as a central feature of each historical case.

This distinction is fundamental for contemporary military institutions.

Scientific knowledge does not enter operational planning automatically. It must pass through a series of institutional functions. Thes functions are listed here:

hazard recognition → scientific evaluation → translation into operational meaning → communication through an authorized channel → comparison of alternatives → command decision → monitoring and reassessment.

Failure to incorporate into the decision making planning process may occur at any point in this sequence.

A laboratory may identify toxicity without understanding its military application. A company may possess production information without a duty or reliable channel to communicate it. A technical report may reach an organization but not the officials responsible for operational planning. A risk may be reported but described in terms that appear uncertain or irrelevant to immediate mission objectives. A commander may receive information without access to the expertise required to interpret its long-term significance.

Predictive Environmental Health Risk Assessment must therefore be designed not only as a scientific procedure but also as an institutional pathway for evidence.

3.4 Decision-making under incomplete knowledge

It would be historically and professionally unrealistic to assume that civilian or military leaders could have predicted every consequence later associated with the herbicide programme. Decision-makers operated within the scientific knowledge, political conditions, military doctrine, institutional culture, and strategic pressures of their time.

The purpose of examining the case is therefore not to reconstruct past decisions according to current knowledge or to assign simplified retrospective blame. Its value lies in identifying how decision systems can be strengthened when evidence is incomplete but the potential consequences are serious.

A predictive approach should require decision-makers to ask:

- Is the proposed material environmentally persistent?
- Can it move through soil, sediment, surface water, groundwater, air, or food chains?
- Can repeated application create cumulative contamination?
- Are degradation products more persistent or toxic than the original material?
- Which civilian or military populations may be exposed?
- Could exposure continue after the operation has ended?
- What data are uncertain or missing?
- What alternatives could achieve the operational objective with lower long-term risk?
- What environmental monitoring should begin before, during, and after use?
- What conditions would require suspension, modification, or reassessment of the activity?

These questions do not guarantee that harm will be prevented. They improve the probability that long-term consequences will become visible before a decision is irreversible.

The professional standard is therefore not perfect prediction. It is the documented consideration of plausible long-term consequences using the best evidence available at the time.

3.5 The Vietnam case as a test of institutional capability

Viewed through this framework, the Vietnam herbicide programme becomes more than a historical account of contamination. It becomes a test of the capabilities that contemporary military institutions require.

Understanding cultural norms, institutional incentives, and personal values is important when examining how scientific information moves through organizations. The historical hypothesis advanced in this case is that the decision to use these herbicides may not have been fully informed because organizational culture, commercial interests, military priorities personal judgement or other sociological and psychological factors affected the flow and interpretation of information available to decision makers (24). The analytical purpose is not to assign motives retrospectively, but to identify institutional conditions that can impede the free flow of relevant knowledge. Understanding these conditions is important for designing systems that allow leadership to use scientific evidence while protecting civilian and military personnel under wartime conditions.

Understanding cultural norms and personal values of institutions and leaders is critical to understanding the accident of President Kennedy's Agent Orange decision. The premise, if accepted that this executive decision to use these herbicides was not fully informed because of business and military decisions biased in cultural or personal values, arrogance or greed prevented the flow of information to make sound judgements based on science is central to the hypothesis (24). Documentation of these human failings in the 60's is lost, but in the late70's U.S. court proceedings are on record against the oil jobber that sold dioxin contaminated oil to control dust on horse arenas,

a landowner burying truckload barrels of dioxin contaminated residuals for an herbicide plant and the plant's foreman and company for authorizing (25). Thus, understanding the cultural norms and personal values of institutions and leaders is critical to ensuring the free flow of knowledge and accurate information so it can be used by leadership to advance the interests of their people while protecting civilian and military personnel in wartime conditions.

President Kennedy's firsthand knowledge of Southeast Asia was from one trip as a Senator. His worldly education and military experiences led him to an incremental approach to military decisions including using neutrality for Laos and Cambodia. An operational error in this author's opinion. Military leadership opinions were dominant during the Kennedy administration and the President Johnson administration as well. Military influence in 1965 produced the adage "Bomb them back into the Stone-Age" and is credited to General Le May, Chief of Staff U.S. Air Force. His advice was influenced by his WWII success (24). Not until scientific advocates led by bioethicist, Arthur Galston urging President Nixon to stop the use of Agent Orange, did the miliary stop using Agent Orange (27).

Historical efforts to regulate chemical and biological warfare developed through a sequence of international initiatives after the First World War, including the 1925 Geneva Protocol. The relationship among early arms control government alliances, permitted research, resulting in treaty development, and subsequent attempt to control use of chemical or biological agents has been historically and legally complex. Thus, should not be considered to be simple one causal conditions (28). the purposes of this paper, the relevant institutional point is that formal rules alone do not guarantee effective prevention; scientific knowledge, monitoring, professional responsibility, and decision-making systems remain necessary.

The case reveals the importance of at least seven institutional functions:

1. early recognition of environmental persistence;
2. integration of industrial, toxicological, ecological, and medical evidence;
3. communication between civilian science and military planning;
4. assessment of cumulative and delayed exposure pathways;
5. comparison of operational alternatives;
6. long-term environmental and health monitoring;
7. institutional mechanisms for revising decisions as evidence changes.

These functions are not limited to herbicides or chemical warfare. They are relevant whenever military operations involve fuels, solvents, firefighting chemicals, combustion products, mining residues, destroyed industrial facilities, contaminated water systems, munitions constituents, waste-disposal sites, or other materials capable of persisting beyond the immediate operation. These broader environmental concerns evident when from the reviewing the field observation of contemporary environmental health concerns which reinforces the historical evidence just made. Working within the military's culture furthermore becomes evident as necessary to understand for implementation of a predictive environmental health risk assessment program to be effective

4 Contemporary Military Operations and Predictive Environmental Risk Assessment

4.1 Working Within Military's Culture

Military leaders' responses to environmental-health risks continue to remain uneven and often are reactive solutions when relevant expertise or information is not incorporated early into operational planning. The Karshi-Khanabad (K2) case illustrates the consequences that can arise when environmental hazards are recognized only after deployment. The former Soviet air base in Uzbekistan, used by U.S. forces to support operations in Afghanistan, was reported to be contaminated, but the environmental assessment was made a year after occupied. The legacy left by the Soviet era contamination was buried chemical weapons, enriched uranium munitions, spilled fuels, solvents, and other hazardous materials. The air and environmental assessments identified multiple potential exposure concerns. Published and official sources cited in this paper report elevated tetrachloroethylene, residual chemical hazards as cyanide, petroleum-hydrocarbon exposure concerns, and an Army study made ten years after leaving the base reporting a substantially increase likelihood of cancer among exposed veterans (29).

An example of how military cultural norms and values can be taken into consideration and lead to good outcomes was the military success of a U.S. brigade in Iraq. A brigade (BDE) was requesting an alternative redeployment movement plan with higher command to reduce hazards to personnel being exposed to sniper fire. The force protection required for a BDE size road march though Ramadi was not practical during a BDE redeployment. A proposed alternative was to build a new marshalling area within the protected base just west of Ramadi. Then the loaded equipment would be moved at night while personnel was air lifted out at the same time. Force protection would fall to the new BDE using the old marshalling area to organize and take over the mission. The decision in Ramadi, Iraq to request change in the troop movement method was based on the military risk assessment. It was observed that every patrol leaving the city center was engaged within six to eight seconds. Thus, to move 1,000 pieces of rolling stock through the city to reach the redeployment railhead, the BDE would have sustained unnecessary casualties. A plan to build a second marshalling area within the protected base was presented to higher command as both practical in available time and at a lower risk. There was one critical human factor observed to determine credibility to support the alternative movement. It was command's concern for personnel and BDE leadership's willingness to take the case to its higher command. (30)

This memorial, was observed during the onsite review for the alternative movement plan. The welded steel material, design, and depiction of images reflected the unit's home state, Pennsylvania. Fitting for the 76 fallen of the 2-28 BDE Soldiers. While at the Ramadi Forward Operation Base personnel came under rocket fire nightly. The patrols out of the city center reported to come under fire within 6-8 minutes. Conducting an inspection, during the day, of two adjoining marine bases, Snake Pit and Hurricane Point, the areas being inspected came under fire 30 minutes after each site

inspections, from mortar attacks, after each site inspection. All of these indicators and the fore noted observations of the brigade leadership, helped rate the risk to base a final recommendation to higher command to approve building a second marshalling area.

Another scenario, with environmental considerations and example of cultural norms happened ten years prior in the Bosnia-Herzegovina campaign. A water packaging operation using a military reverse osmosis purification and a new packaging machine needed a production site. An existing Quonset shed, already under Army contract was evaluated. The site was on an agriculture cooperative and still available for use since it was February, the off winter season. Due to snow cover little of the grounds could be observed. A few cattail heads were noticed to one side of the shed and on the other side were circler concrete pads of undetermined purpose, hidden from inspection under snow cover. The Agriculture Cooperative's office had useful information from photos displayed on the hallway wall depicting the services provided by the operation. One photo showed a helicopter spraying and another was from an overview of the facility. Asking the manager what the pads use was, he disclosed the pads were for helicopter cleaning after spray runs. The photos showed drains, in the concrete pads which collected the wash water, which then ran in a shallow drainage ditch to the wetland near the cattails. The environmental assessment was there would be impact on humans, herbicide residues possibly entering the water packaging operation, from the pesticides in runoff from the helicopter cleaning pad. Also, the mosquito control spraying on the wetland was a concern.

The observed Ramadi 2-28 Brigade commander's concern for his soldiers was based on subjective observation arrived at when seeing the memorial, construction approved by the BDE Commander, to the 76 fallen soldiers. The BDE staff's claim of the number of seconds before patrols being engaged was verified by interviewing company level patrol leaders. Plus, on the ground cross checking with Soldiers, Marines and the easy and rapidity the bases were brought under motor and rocket artillery fire. However, during interview of the Agricultural Cooperatives Manager's case was less apparent. The Cooperative Manager was not forth coming in disclosing any hazards. Rather the onsite observations made, supported by knowledge of the chemical spraying and cleanup hazards, were the critical element that counter the manager lack of forthrightness in disclosing the environmental hazards. He, apparently only wanted the U.S. military contract, thus disclosed minable information. The inspection had to have prior knowledge to actuality assess the environmental health risk. (30)

A third example was designed by the 10th Mountain Division Commander, Major General James Terry, 2009-2010, who orientated his division staff's training for Afghanistan around the civilian and military cultures. During the training, at Fort Drum, New York, a real world scenario occurred 6,500 miles away. This depicts how including specialist's viewpoints with the military planning process can work. A validation for the Predictive Environmental Health Risk Assessment for Military Operations.

One of the 10th Mountain Divisions units, already in Afghanistan was establishing a new Combat Outpost (COP) and reported an issue with the village elders. Qanat

tunnels and shafts built by a group of skilled laborers called muqannis had manhole shafts entering the developing COP. The skill to maintain the Qanat tunnel has been passed down from father to son and goes back several generations. The muqannis were key figures in the village leadership. The Qanat tunnel shafts were used to enter the tunnels for maintenance. US military planners in Afghanistan had missed the detain these shafts leading into the middle of the COP had a purpose ensuring irrigation water, delivered from the Karez irrigation system for crops and was critical to the livelihoods of the Afghanistan people and their village's survival. The result of the oversight, as a force protection measure, the shafts were filled in. The Division Commander had a full time Anthropologist on his special staff whom picked up there was a problem with the new COP. Also there, were other civilian specialists, (30) whom had been brought in through the Department of State to support the Division Staff training. One, an irrigation specialist, picked up on the Karez tunnel irrigation system connection. The military rather than trying to understand the civilian's utility of the shafts was for irrigation maintenance and then working with the local leaders to resolve any security issues, the shafts were closed to achieve security. The understanding that the Qanat tunnels and shafts were an essential part of the irrigation system required to grow crops came afterward due to having specialists available to inform leaders. Late, but in time to avoid substantial harm to the civilian food production. Today if the Predictive Environmental Health Risk Assessment is made part of military planning by having the advice of specialists readily on hand this could reduce future health risks in the area of operation.

These three examples have the military decision points clearly identified to avoid long term harm. This is not the case when looking for the decision that led to occupying Karshi-Khanabad 2001-2005, the Soviet military base in Uzbekistan to support operations in Afghanistan. Nor was there an infrastructure to research and inform decision makers during the Vietnam planning before the large build up in 1964. These single failures to identify risk hazards ahead of decisions affected our past Veterans from Vietnam and recently impact on the health of service men and women from burn pits and K2 has resulted in new congressional legalization found in Honoring Our PACT Act (2022) 38 U.S.C. § 1119.

These military experiences therefore supply empirical evidence for a broader proposition:

Military environmental-health risk is created not only by hazardous materials, but also by the absence of institutional systems capable of connecting scientific knowledge to operational decisions.

4.2 From historical and contemporary evidence to prospective institutional design

Historical research becomes operationally relevant when it changes the design of future institutions. Additional insight into how operational feasibility came from a recent interview professional interview with Lieutenant General James L. Terry (Ret.). General Terry, former commander of the 10th Mountain Division, is currently Senior Vice President, Superintendent Cadet Leadership Academy of University of North Georgia. His comments are used here as professional testimony concerning the

requirements of doctrine driven military planning and operations could integrate additional risk assessment information.

General Terry stated, “military planners and leaders want to make the right decision. The challenge is having the information necessary to integrate into a doctrine driven organization within the time constraints of any given operation.” General Terry, in his career had experience with the health hazards from burn pits when stationed in the Sinai. Later, as the regional command operations officer, felt, “planning entailed arriving at judgements made by balancing the requirements of doctrine driven management based on; what is the cost? What resources, lives and the degree or outlook forecast of mission success.” In discussion it was recognized that on the battlefield and in the support areas remnants of depleted uranium and any number of environmental health hazards could be left. The spectrum of hazards ranges from improperly disposed munitions, and petroleum products to discarded chemicals and medical products. As a Soil Scientist, this author sees mapping the location of these hazards is only first step. Transportation of the residuals by water erosion and also wind erosion’s fine dust particles and the saltation of larger grains migrate from original deposits are landscape and weather dependent. These physical characteristics further complicate the development of a ‘tool’ for environmental health risk assessment. Force protection remains the military planners mandate to ensure accomplishment of follow-on missions. “Integration of Environmental Health Risk Assessment as part of a decision process would be welcome”; General Terry felt, “once the tool was developed that fits in with military planning process.”

The principal contribution of the Vietnam and other military operation cases is not simply the recognition that environmental contamination occurred. That conclusion is already well established. Its greater value is that it identifies the types of information, expertise, institutional channels, and decision procedures that must exist before comparable risks arise in future operations.

Predictive Environmental Health Risk Assessment should therefore begin before material selection or operational deployment. It should continue through planning, implementation, monitoring, and post-operation evaluation. New evidence should be capable of reopening earlier assessments rather than remaining separated from command procedures.

Environmental risk assessment, looking at the long term operation effects on the landscape and those living there, should be part of risk assessment training. This would then be a military’s version along the lines of Arthur Galston’s moral responsibility encapsulated by his science bioethics coursework. The objective to instil in the thought process of military planners to consider the environmental impact of tactical decisions. By making bioethicist coursework part of risk assessment planning leaders, at all levels, military, science and business industry, will find it beneficial to be part of protecting the environment for humans. Informing the public of hazards is critical to finding best solutions. By integrating all three viewpoints, military, business-industry, and science, considering both the long term risk against the immediate objective exceptions decisions should result. Part of finding better solutions is equipping our

leaders with skills to avoid damaging the environment. This approach, if adopted widely, will make a measurable difference in protecting the environment for humans.

This approach changes the role of environmental science within military institutions. Environmental expertise is no longer limited to regulatory compliance, remediation, or documentation after damage occurs. It becomes part of operational design.

Under this model, environmental scientists and public-health specialists do not make military decisions. Commanders retain responsibility for balancing mission requirements, personnel protection, uncertainty, and competing risks. Scientific expertise provides the evidence necessary for those decisions to be professionally informed.

The institutional objective is therefore not to transfer command authority to technical experts. It is to ensure that command authority is exercised with access to evidence concerning consequences that may otherwise remain invisible during the period of immediate operational action.

5. Recurring Institutional Patterns in Military Environmental Risk Assessment

5.1 Why comparative operational evidence matters

Historical military operations differ in geography, political context, military objectives, technologies, and environmental conditions. At first sight, comparisons among Vietnam, Bosnia-Herzegovina, Iraq, Afghanistan, or other operational environments may appear limited because each conflict presents unique circumstances.

From the perspective of Predictive Environmental Health Risk Assessment, however, the principal scientific value of these cases lies elsewhere.

Rather than examining individual conflicts as isolated historical events, this paper treats them as independent observations contributing to a broader understanding of environmental decision-making under operational conditions.

The objective is therefore not historical comparison itself. It is the identification of institutional processes that recur across different operational environments despite substantial differences in geography, technology, political objectives, and military doctrine. Every assessment should integrate environmental toxicology, exposure science, epidemiology, ecosystem monitoring, bioethics, institutional communication, and local environmental knowledge

If comparable environmental decision-making patterns repeatedly emerge across independent military operations, these recurring observations may reflect structural characteristics of military institutions rather than unique historical circumstances.

For this reason, the following operational examples should not be interpreted as equivalent environmental disasters or identical military experiences. They represent independent sources of evidence through which common institutional characteristics become observable.

5.2 Environmental hazards become visible through different pathways

One recurring observation emerging from multiple operational environments is that environmental hazards rarely become visible through a single source of information. Some hazards are identified through formal scientific investigation. Others become apparent through routine environmental observation. Still others emerge through local ecological knowledge, operational experience, engineering practice, medical surveillance, or conversations with local communities.

Consequently, environmental risk assessment depends not only upon scientific expertise but also upon the institutional capacity to recognize, integrate, and evaluate multiple forms of evidence.

Professional judgement frequently begins before laboratory confirmation becomes available.

Observable environmental indicators, unusual ecological conditions, damaged infrastructure, unexpected contamination pathways, or inconsistencies between expected and observed environmental conditions often provide the earliest signals that additional scientific investigation is required.

The ability to recognize such indicators represents an important professional competence rather than an alternative to scientific analysis.

5.3 Information exists before institutions recognize it

A second recurring institutional pattern concerns the relationship between available knowledge and operational decision-making.

Scientific evidence rarely appears suddenly. More commonly, relevant information exists in fragmented form long before it influences institutional decisions.

Industrial observations, environmental monitoring, toxicological studies, engineering reports, medical findings, operational experience, and local environmental knowledge may all exist independently without becoming integrated into a common assessment.

The central institutional challenge therefore concerns integration rather than discovery alone.

Predictive Environmental Health Risk Assessment assumes that the scientific problem is frequently not the complete absence of information but the inability of organizations to assemble separate observations into operationally meaningful evidence.

Military institutions consequently require mechanisms capable of identifying incomplete information, recognizing emerging patterns, and communicating scientifically relevant uncertainty before irreversible decisions are implemented.

5.4 Environmental evidence must become operational evidence

Scientific knowledge contributes to military planning only after it is translated into operational language.

Environmental persistence, contaminant mobility, ecological recovery, food-chain transfer, groundwater vulnerability, or chronic human exposure may be scientifically well understood while remaining operationally invisible if these processes are not interpreted within military planning procedures.

Predictive Environmental Health Risk Assessment therefore requires an intermediate stage between environmental science and military decision-making.

Environmental evidence must first become operational evidence.

This transformation involves interpreting scientific findings in terms relevant to commanders:

- operational implications;
- exposure duration;
- vulnerable populations;
- environmental persistence;
- uncertainty;
- alternative operational options;
- monitoring requirements;
- long-term mission consequences.

The scientific question is therefore no longer simply: "What does environmental science tell us?"

It becomes: "What environmental information is operationally relevant before this decision is implemented?"

5.5 Institutional learning rather than historical lessons

The recurring patterns identified across multiple operational environments suggest that military organizations should move beyond the traditional concept of historical lessons.

Historical experience does not automatically improve future decision-making.

Institutional learning occurs only when organizations modify professional education, operational procedures, reporting systems, risk assessment methods, and command processes in response to accumulated evidence.

For this reason, the objective of historical analysis is not the extraction of lessons in the conventional sense.

Its objective is institutional adaptation. Each documented environmental case contributes additional evidence concerning how scientific knowledge can become more effectively integrated into operational planning.

The cumulative value of these observations lies not in reconstructing the past but in improving future institutional performance.

5.6 Environmental risk as a component of professional military competence

These recurring institutional observations suggest a broader interpretation of professional military competence. Military leaders have traditionally been educated to

evaluate operational effectiveness, force protection, logistics, intelligence, maneuver, and mission accomplishment.

Contemporary operational environments increasingly require an additional capability. Professional military judgement must also include the ability to recognize when environmental science, public-health evidence, toxicology, ecology, epidemiology, engineering, or local environmental knowledge become essential components of operational planning.

This does not imply that commanders become environmental scientists. Rather, it requires commanders to recognize when environmental expertise materially influences operational decisions and to ensure that appropriate scientific evidence enters the decision process.

The proposed framework therefore expands professional military competence without altering the fundamental responsibility of command.

Scientific expertise informs decisions. Command responsibility remains with military leadership.

5.7 From recurring observations to Predictive Environmental Health Risk Assessment

Taken individually, the operational examples discussed in this paper represent independent historical observations.

Taken together, they reveal recurring institutional patterns concerning hazard recognition, environmental observation, information integration, professional judgement, organizational communication, and command decision-making.

These recurring patterns provide the empirical basis for the next stage of this study.

Rather than treating environmental contamination as a consequence to be investigated only after military operations have concluded, Predictive Environmental Health Risk Assessment proposes that environmental-health evidence should become an integral component of operational planning before military activities capable of producing long-term consequences are undertaken.

The following section therefore presents an initial conceptual framework intended to organize these recurring institutional observations into a coherent approach for future military environmental risk assessment.

Scientific evidence becomes operationally useful only when institutions can identify, evaluate, communicate, and incorporate it into command decision-making.

6. Toward a Working Framework for Predictive Environmental Health Risk Assessment

6.1 From environmental science to professional military practice

The preceding sections suggest that Predictive Environmental Health Risk Assessment should not be understood as a single analytical technique or an extension of existing environmental assessment procedures. Rather, it represents an emerging

interdisciplinary framework through which environmental science may become an integral component of professional military practice.

The objective is not to transfer operational decision-making from military leadership to scientific experts. Military decisions necessarily involve strategic, operational, political, humanitarian, logistical, and legal considerations that extend beyond environmental science alone. Scientific evidence becomes operationally useful only when institutions, military, can identify, evaluate, communicate, and incorporate it into command decision-making. As Lieutenant General Terry stated, military leaders want to make the right decision, the challenge is getting the necessary information timely.

The objective for using the Predictive Environmental Health Risk Assessment tool is different from transferring the responsibility, but making the scientific evidence operationally effective.

It is to ensure that scientifically relevant knowledge concerning potential environmental and public-health consequences becomes available, understandable, and operationally meaningful before military decisions are implemented.

Within this perspective, environmental science does not replace military judgement. It strengthens sound professional military judgement.

6.2 Scientific knowledge as an institutional process

The historical and operational evidence reviewed in this paper suggests that environmental knowledge should not be viewed simply as scientific information generated by researchers.

Knowledge becomes operationally relevant only after it passes through a sequence of institutional processes. Scientific observations must first be recognized as potentially significant.

Relevant evidence must then be evaluated, interpreted, communicated, integrated into operational planning, considered alongside alternative courses of action, and subsequently updated through environmental monitoring.

Failure at any stage of this sequence may substantially reduce the practical value of otherwise reliable scientific evidence.

Predictive Environmental Health Risk Assessment therefore concerns institutional knowledge management as much as environmental science itself. The central question is no longer whether scientific knowledge exists. The central question becomes: How can institutions ensure that available scientific knowledge contributes effectively to professional military judgement?

7. Framework of an Operational Tool for Predictive Environmental Risk Assessment

7.1 Components of the working framework

The present study proposes six interconnected institutional components that together constitute a preliminary working framework for Predictive Environmental

Health Risk Assessment. Again, as stated in the key objectives for this paper; the purpose of the proposed framework is not perfect prediction, but better-informed professional judgement under conditions of uncertainty.

Environmental intelligence. Relevant scientific knowledge should be collected from multiple complementary sources, including published research, environmental monitoring, toxicological investigations, epidemiological evidence, engineering assessments, industrial experience, previous military operations, and local environmental knowledge.

No single source is expected to provide a complete assessment. Rather, environmental intelligence emerges through the integration of multiple forms of evidence.

Scientific interpretation. Available information should then be interpreted in terms of environmental persistence, contaminant transport, exposure pathways, ecological vulnerability, uncertainty, knowledge gaps, and potential long-term human-health consequences.

The objective is not to eliminate uncertainty but to identify scientifically plausible environmental scenarios requiring professional attention.

Operational integration. Scientific findings become operationally meaningful only after inclusion into military planning.

Environmental evidence should therefore be interpreted in relation to operational alternatives, mission objectives, force protection, civilian populations, environmental persistence, monitoring requirements, and post-conflict recovery. This stage represents the principal interface between environmental science and military planning.

Command support. Military commanders remain responsible for operational decisions.

Scientific expertise contributes by providing structured evidence concerning environmental and public-health consequences that may otherwise remain outside immediate operational awareness.

Predictive Environmental Health Risk Assessment therefore functions as a decision-support process rather than a decision-making process.

Adaptive environmental monitoring. Environmental assessment should continue throughout planning, implementation, and post-operational phases.

New scientific evidence may require reassessment of previous conclusions.

Monitoring therefore serves not only documentation purposes but also continuous improvement of institutional knowledge. Environmental assessment becomes an adaptive rather than static process.

Institutional learning. The final component concerns institutional adaptation.

Professional military organizations improve not simply by accumulating historical experience but by incorporating validated scientific knowledge into doctrine,

professional military education, operational planning procedures, environmental governance, and organizational culture.

Historical evidence thereby becomes part of institutional capability rather than remaining a record of past events.

7.2 Professional military education

The proposed framework suggests an expanded understanding of professional military education.

Military officers are already trained to evaluate operational uncertainty, assess probability and severity, compare alternative courses of action, and make decisions under conditions of incomplete information. Risk assessment decision matix is used by entry level officers during training. For complex plans deliberate risk assessment forms and procedures are used.

Better risk assessment, report training, and processing of environmental hazards are needed by military leadership and also scientists and engineers working for businesses that produce military equipment and supplies. These environmental inclusions to the risk management training process while new to existing military doctrine would not necessarily follow Arthur Galston's Yale bioethics course curriculum, but a curriculum written for the military. Rather other considerations for military objectives would be necessary to balance risk and force protection considerations. Still, with these concessions, there would be room for the argument that training scientists and business executives using the bioethics academic curriculum would be acceptable for those non-military institutions. Integrating new environmental assessment models with the established military methods as the DOD MIL-STD-882E chart, a simple, small pocket size, color coded with green, yellow, red, threat level blocks, laminated for field, card shows the use of Risk Assessment Matrices is one method which should be adopted with an environmental health risk assessment military curriculum. (31)

Training on risk assessment starts early for military leaders starting at basic enter level and continues throughout their career. More training to recognize environmental hazards is needed. Further there is a need to stress system processing of reports in order to ensure decisions are informed by the best available information and passed forward through the chain-of-command. Failure to ensure decision makers are informed has been the critical juncture in the U.S. military institution system processes. Often assessment results that are not passed forward have been of environmental damages that impact humans. In the 50's and 60's, early in the Vietnam War, there was not a system or institution connecting private research with the biotesting government labs in Fort Detrick, MD. (24, 27) Economic, military and political cultures and values can create a drag on institutional systems devised and prevent information deemed undesirable from flowing to military and civilian decision makers. Thus, only creating the system is not enough. The social, economic, and political culture and norms must be revealed and understood to find the hidden information, facts and biases that underly information provided to the system in order to make well-informed assessments leaders require to make good decisions.

Predictive Environmental Health Risk Assessment does not replace these competencies. It extends them.

Future military leaders may increasingly require the ability to recognize when environmental science, toxicology, epidemiology, engineering, ecology, or local environmental knowledge become operationally relevant.

Equally important is the ability to recognize the limits of available evidence, identify missing information, request appropriate scientific expertise, and communicate uncertainty within command processes.

Professional competence therefore includes not only making decisions under uncertainty but also recognizing when additional scientific knowledge may materially improve those decisions.

7.3 An emerging research framework

The framework presented here should be regarded as an initial conceptual contribution rather than a completed operational methodology.

Its purpose is to provide an organizing structure through which environmental science, public health, military planning, operational risk assessment, environmental governance, and professional military education may gradually become integrated into a common institutional process.

Future research should examine the practical implementation of individual framework components, evaluate their effectiveness under operational conditions, and refine the framework through comparative analyses involving different military organizations, environmental settings, and conflict environments.

The framework is therefore intended not as a final model but as a foundation upon which a broader interdisciplinary research programme may progressively develop.

8. Conclusions

The historical cases discussed in this paper demonstrate that long-term environmental and public-health consequences associated with military operations cannot be understood solely through retrospective environmental assessment. They also reveal a broader institutional challenge: scientifically relevant environmental knowledge may exist without becoming an effective component of operational decision-making.

The principal contribution of this paper is therefore not a reinterpretation of the Vietnam War or other individual military operations. Rather, these historical and operational observations are used to identify recurring institutional patterns that remain relevant for contemporary military organizations. Across different operational environments, similar challenges emerge concerning hazard recognition, environmental observation, scientific communication, organizational learning, and the integration of environmental evidence into command decision-making.

These recurring observations suggest that environmental risk should be regarded not simply as a technical or regulatory issue, but as an integral component of professional military competence. Effective environmental protection during military

operations depends not only upon advances in environmental science but also upon institutional processes capable of identifying, interpreting, communicating, and operationally applying scientific knowledge before potentially irreversible environmental consequences occur.

For this reason, the paper proposes an initial working framework for Predictive Environmental Health Risk Assessment. The framework is not presented as a completed methodology or a validated operational model. Instead, it represents a conceptual starting point for the systematic integration of environmental science, public health, operational planning, environmental governance, and professional military education.

The objective of Predictive Environmental Health Risk Assessment is not to eliminate uncertainty from military decision-making. Such an objective would neither be realistic nor consistent with the realities of military operations. Rather, its purpose is to improve professional judgement under conditions of uncertainty by ensuring that the best available scientific evidence concerning potential long-term environmental and public-health consequences becomes available before operational decisions are implemented.

Future research should therefore move beyond retrospective documentation of environmental damage and concentrate on developing practical institutional mechanisms capable of incorporating environmental knowledge into military planning. This includes methodological development, comparative operational research, professional military education, environmental intelligence, adaptive monitoring, organizational learning, and international scientific collaboration. Scientific knowledge does not make military decisions. Military leaders do. The continuing challenge for both science and military institutions is to ensure that professional judgement is informed by the best environmental evidence available before action is taken.

Environmental pollution associated with military activities represents one of the most complex interdisciplinary challenges confronting contemporary science. Addressing this challenge requires closer cooperation between environmental scientists, toxicologists, epidemiologists, engineers, military educators, operational planners, and decision-makers. The long-term objective is not simply improved environmental assessment after conflict, but the progressive incorporation of scientific knowledge into professional military practice before environmental harm occurs.

In this sense, Predictive Environmental Health Risk Assessment should be viewed not as the conclusion of an existing field of research but as the beginning of a broader interdisciplinary programme linking environmental science, public health, and military decision-making. Scientific knowledge does not make military decisions. Military leaders do. The continuing challenge for both science and military institutions is to ensure that professional judgement is informed by the best environmental evidence available before action is taken.

For scientists wanting to pursue the development of Predictive Environmental Health Risk Assessment with the military better understanding of language of military doctrine is recommended. One source to improve understanding can be found in JP 1,

Doctrine for the Armed Forces of the United States. Other countries will have similar references.

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Conflict of Interest

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Note: Interview with Lieutenant General James L. Terry was conducted on Thursday, August 20, 2026 at 10:00 AM Central using Teams. Review drafts to check accuracy were sent 8/24/26 of paper and corrected sections paper and slide deck on 9/8/2026.