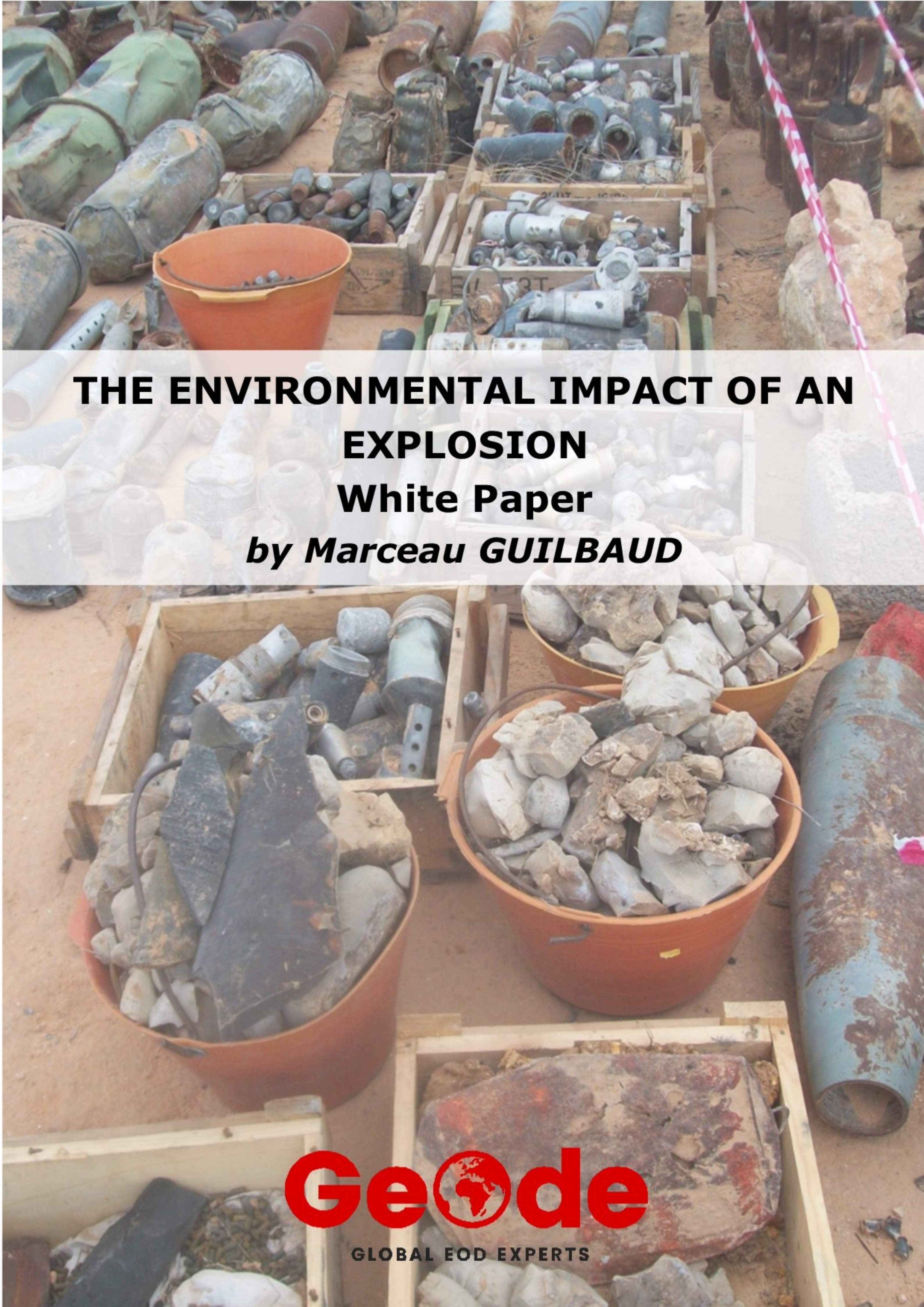

THE ENVIRONMENTAL IMPACT OF AN EXPLOSION

White Paper

by Marceau GUILBAUD

Geode

GLOBAL EOD EXPERTS

« Following my military career, I committed to humanitarian mine action, then to physical security and stockpile management and at last, to the reduction of armed violence.

During several missions, I have seen that the international community has never taken into account the environmental problems of explosive pollution caused by the presence of conventional unexploded or abandoned explosive ordnance.

I also realized that the initiative to clear areas was only based on both the risk of explosion and the assessment of socio-economic impacts of this contamination.

However, although there is a lack of scientific validation, it is essential to consider that the more the decontamination of an area is delayed, the greater the probability of an impact on the environment and the food chain.

Finally, the systematic use of on-site demolition causes localized pollution of the soil which will not be remedied later. It would therefore be necessary to prioritize demolition-sites, after the temporary storage and displacement to that site for bulk-demolition. Ultimately, in-situ demolition would be reserved for dangerous non-displaceable ammunition. »

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…THE IMPORTANCE OF RAPID REMEDIATION OF AREAS POLLUTED BY EXPLOSIVE AMMUNITIONS…

Introduction

I – Normalization

This chapter offers a review of the different normative documents dealing with pyrotechnical depollution and the obligation to take sustainable development into account.

II – Overview

Using the case of the MISURATA ammunition depot in Libya, this chapter defines the non-pyrotechnical risks of pollution by explosive materials, due to the unexpected explosion of an ammunition storage facility. The pollutants are mainly heavy metals and chemical molecules.

III – Health Impact

This chapter provides an assessment of the health impact, on a more or less long term, of lack of soil remediation, through a review of available documentary resources, showing the direct impacts of pollutants defined in the first chapter on life cycles and the food chain.

IV – Completed Clearance

This chapter offers a review of the requirements for comprehensive remediation of an area polluted by chemical components. This remediation must include the pyrotechnical risk and at a sufficient depth in order to remove the non-pyrotechnical pollutants as much as possible.

V – Soil Remediation

This chapter provides a non-exhaustive review of the least expensive soil remediation methods.

Conclusion

References

Introduction

Source: Misrata depot after bombing – Libya © Marceau Guilbaud

The purpose of this white paper is to demonstrate that clearance carried out after an Unplanned Explosion at Munitions Sites (UEMS), or of a confirmed hazardous area (CHA) polluted by Explosive Remnants of War (ERW) or improvised explosive devices (IEDs), must not only take into account the explosive hazard but also the impact on the environment and on the living in general.

An unplanned explosion of an "official" ammunition site can be caused by poor storage, non-compliance with the rules for the physical security of stocks, a fire or by a violent external event such as an armed, terrorist attack or aerial bombing for instance.

Accidental explosions can also occur in "unofficial" ammunition storage facilities, or in areas polluted by individual or grouped explosive ordnance, unexploded, abandoned or used as improvised explosive devices.

Small Arms Survey (SAS)[1] defines unplanned explosions at munition sites (UEMS)[2] "*as accidents that resulted, individually, in dozens of casualties and millions of dollars in damage within the depot itself, but also for its immediate surrounding environment. SAS studies have recorded, between 1979 and 2019, 623 incidents in at least 106 countries around the world with a very clear increase in the number of accidents since 2016*".
"*Among the 106 UEMS that have claimed the most victims since 1979, 72 occurred in or near a residential area, big city, community, slum, suburb, small town or village.*"[2]

In general, the studies carried out take into account the destructive effects of the explosions on human beings and on property, but not the environmental impacts of such incidents, whether there has been clearance or not.

This white paper also wants to include pollution by explosive remnants of war (ERW) and IEDs. Indeed, in addition to the explosive hazard of these threats, there is an environmental risk due to the physical and molecular degradation of these dangerous devices, which increases over time.

Some developed countries have implemented soil remediation and relevant procedures to tackle pollution from munitions but only at the national level. For example, in the United States, the Department of Defense (DoD) disposes of an annual budget to deal with all pyrotechnic incidents which pose an environmental risk to populations.[3]

Very few countries take this risk into account and put in place financial means to remedy the soils polluted by explosives accidents, such as hydrocarbon accidents

The international community and institutional mine action donors do not provide funding for soil remediation projects. In addition, the international organizations for mine action, or Weapons and Ammunition Management (WAM), are not requesting to pay attention to the past years where they declared sites decontaminated without ever have taken this issue into account. This lack of interest results from a lack of knowledge of the problem, and of the impacts, because few serious studies have been carried out on this subject.

The author of this report will illustrate his point based on a study he conducted in the past in Libya on the MISURATA ammunition site, which was bombed by NATO forces, resulting in the destruction of all igloo-type storage magazines covered with earth designed to withstand an internal overpressure of 3 Bars.

The bombardment completely destroyed the structures of the depot and caused the dispersion of ammunition which had suffered from external damage, due to heat, projection and impact with the ground. These explosions created serious damage to the internal and external structures of the munitions, resulting in the projection of initial fragments carrying heavy metals and chemical elements, on the surface and underground but at a shallow depth.

The author also draws on other observations made in the TOBRUK region (Libya) and in Chad, at a poorly maintained shooting training site, as well as in the Democratic Republic of Congo (DRC). Unfortunately, having very limited means to undertake scientifically indisputable assessments, he had to be content with conducting interviews with medical officials from TOBRUK and MISURATA, regional politico-administrative officials in Chad as well as interviews with women farmer's in the DRC to obtain contextual elements proving the harmfulness of this environmental pollution, which was never taken into account.

Libya was an excellent field of study due to the fact that most of the water used for current consumption comes from the desalination of sea water and its storage in semi-buried reserves. At MISURATA, water storage facilities are located around the ammunition depot. In addition, irrigation of land producing fruit and vegetables is also carried out from these same reserves. In TOBRUK, the study area is located on a hill overlooking the town and the Gulf of TOBRUK. Sheep are reared on this plateau, roaming and grazing on the low vegetation around the open-air storage sites of WWII ammunition. Rainwater carries pollutants in the soil to sea level where the fishing resource is taken by fishermen. Sheep and fish are consumed by the inhabitants of TOBRUK.

In Chad, the shooting range was surrounded by two traditional villages which supply the population with drinking water.

In all of these cases, death rates have been found to be higher than elsewhere in the country, without any chemical pollution study being able to be carried out to analyze the causes.

In the DRC, visiting an uncultivated land after clearance, the owner declared that "nothing was growing anymore!"

This report should provide elements for reflection to enable such assessments to be carried out, which cannot be disputed, with a view to taking the problem into account in the near future since there is real urgency as well as remedial solutions.

It also provides a basis for reflection on the intensive use of in situ destruction of explosive remnants of war, which in fact creates localized soil pollution, but also for reflection on the unacceptable impact of the burning of weapons and ammunition.

Pollution dating from WWII - Battle of Gazala - TOBRUK - Ammunition has thus been gathered for many years in a sheep farm where sheep graze on short grass and where the guards have their living quarters.

Libya. © M. Guilbaud

Anti-vehicle Mine in Bir Hakeim minefields - Battle of Gazala - the case is still present, but the inner explosive has been sublimated by sun heat or consumed by ants, as observed in other countries.

Libya. © M. Guilbaud


Misurata ammunition site after bombing – Libya © Marceau Guilbaud

I - Normalization

On September 25, 2015, the United Nations General Assembly adopted a resolution called "*Transforming the World: The 2030 Agenda for Sustainable Development.*"[4] It defines a set of goals and targets. Article 55 of this resolution defines these sustainable development goals and objectives as follows*:* [.] are integrated and indivisible, global in nature and universally applicable, taking into account different national realities, capacities and levels of development and respecting national policies and priorities. Targets are defined as aspirational and global, with each government setting its own national targets guided by the global level of ambition but taking into account national circumstances. Each government will also decide how these aspirational and global targets should be incorporated in national planning processes, policies, and strategies. It is important to recognize the link between sustainable development and other relevant ongoing processes in the economic, social, and environmental fields [.].

Other standards are also to be used in mine action and physical security of stockpiles of weapons and ammunition to reduce the effects and impacts on the environment and life.

In 2015, the United Nations launched the 2030 Sustainable Development Program defining seventeen (17) goals aimed at "*eliminating poverty, protecting the planet and improving the daily lives of all people everywhere, all by opening up prospects for them.*"[5] In 2019, during the Summit on Sustainable Development Goals, a call to mobilize society was launched, for the remaining decade, in three areas:

- Global action;
- Action at the local level; and
- Action on an individual scale.

The reduction of armed violence, which mine action supports, should contribute to the sustainable development program. Of the seventeen goals defined, mine action, ERW and IED disposal, etc. can address the following objectives:

The depollution of confirmed hazardous areas (CHA) makes it possible to restore arable land, to reopen communication routes, to improve access to trade, health services and schools. This contributes to the achievement of goals 1 to 4:

o No poverty;
o “Zero” hunger;
o Good health and well-being; and
o Quality education.

The inclusion of gender in activities to reduce armed violence helps to recognize the rights of men / women, whatever their age or origins, and to review the expected role in their society. This contributes to the achievement of goals 5 and 10:

o Gender equality;
o Reduced inequalities;

Respect for the environment in the clearance of hazardous areas at all stages, from planning, to land restitution, to the destruction of explosive ordnance, and risk education, should enable the achievement of objectives 6, 12, 13, 14 and 15:

o Clean water and sanitation;
o Responsible consumption and production;
o Climate action;
o Life below water; and
o Life on land.

In accordance with the principles of the ISO 14000[6] series of standards, environmental management concerns:

a) Pollution of air (noise, smoke, etc.), water and soil; Reduction and destruction of waste, in particular toxic and dangerous products;
b) Reducing energy consumption;
c) Reduction of CO_2 emissions;
d) Use of land; and
e) Risks for heritage.

The International Mine Action Standard (IMAS) 07.13 Ed1 - Environmental management[7] defines the following in its introduction: [.] Effective management of environmental aspects of mine action operations is important from the perspectives of mine action operating organizations themselves, affected communities, national authorities, donors and the wider global community. Protection of the environment receives growing attention from national governments and international institutions and is reflected in the increasingly rigorous demands associated with national legislation in many countries and the terms of international treaties. Mine action operations are entirely subject to applicable national environmental legislation and the terms of international treaties.

Mine action improves not only safety and security of population, but also opportunities for socioeconomic development as its aims to "reduce the social, economic and environmental impact of mines, and ERW including unexploded submunitions."[8] Mine action activities have a positive impact on the environment, but this does not remove the potential for negative impacts. It is thus important to prevent and mitigate possible adverse effects through appropriate environmental management which takes into account the specific activities conducted by a mine action organization and the context in which operations are conducted.

Environmental management is meant to strengthen mine action effectiveness and efficiency in achieving its aim. Shortcomings in environmental management in mine action can: reduce or prevent the results and outcomes expected to arise from mine action operations; lead to short and long term adverse effects on land, water, soil and air and the communities living in the vicinity of mine action work sites; result in direct harm to people, damage to the environment and infrastructure; and give rise to legal action against mine action organizations and substantial claims for compensation. Adverse effects on the environment can lead to associated negative social, economic, and political impacts at local, regional, and national levels. Environmental management therefore calls for holistic solutions which assess different impacts and an increased awareness towards environmental protection among all mine action organizations [.]

IMAS 07.13[7] only takes into account the environmental impact of Mine clearance actions but ignores the consequences of the lack of clearance.

Chapter C.3. of Annex C[9] of this IMAS defines the following: "[.] Different chemical compounds from mines and ERW (including unexploded sub-munitions and improvised explosive devices (IEDs)) could dissolve and enter waterways, crystalize into new components in the soil or be incorporated into existing soils and minerals. Being planted on the surface of land or just beneath it, landmines (especially improvised types) most direct impact is on soil quality and composition. Soil can be affected by the casing, explosions or leaking of toxic substances as a consequence of corrosion or decomposition. Consequences of the corrosion of fragments may include the release of various alloy elements such as iron, manganese, chromium, zinc, copper etc. start emerging. A number of toxic and hazardous elements may appear as a pollutant after utilization of high-explosive weapons. In agricultural regions, toxic elements can penetrate the human food chain. Therefore, as toxic elements penetrate the soil, processes of bioaccumulation can start and affect human health. [.]."

Various types of environmental impact are to be considered through the following:

a) Human dejecta;
b) Household waste;
c) Greywater;
d) Flammable, oily materials / waste, lubricants, fuel filters etc.;
e) Batteries and accumulators;
f) Waste from medical care, expired drugs and other chemicals.
g) Etc.

International Ammunition Technical Guideline (IATG) 11.30[10] – Ammunition storage area explosions – EOD clearance, explains the need to clean up ammunition storage sites after an explosion. This standard is introduced by the following reminder: [.]There are a number of examples in the recent past where the post-explosive clearance of ammunition depots has been based primarily on “demining” standing operating procedures (SOP). Whilst this may seem a practical step at the outset, in real terms it is not particularly efficient, or at times even safe. The threat is different, the clearance options much wider, and further technical knowledge is required than that needed for mine and unexploded ordnance (UXO) clearance[.].

IATG 11.30 clearly defines the risks associated with an accidental explosion in an ammunition depot as follows:

a) Ammunition may have been thrown away from the seat of the explosion (we have already observed unguided rockets which have traveled up to 20 km). If the ammunition has been stored primed, it is quite possible that the force of the explosion is sufficient to trigger the primer. Thus, all primed ammunition discovered at the explosion site or at a short distance around it, must be considered as unexploded ordnance (DEM) and treated accordingly;
b) The explosive content of ammunition natures may be either partially or fully burnt out. If partially burnt out, then there will be the normal hazards presented by exposed explosive. Additionally, there may be the hazards associated with melted explosives re-crystallizing and forming undesirable, more sensitive isomers e.g. TNT;
c) Ammunition can be broken, thus exposing active or pyrotechnic materials (white phosphorus, submunitions) which are likely to have been dispersed throughout the site;
d) Ammunition may have been broken open leading to exposed electrical leads;
e) Propellant may not have burnt during the explosion and fires; therefore, exposed propellant may be spread across the site. This may spontaneously ignite during EOD clearance operations; such ignition will be dependent on the chemical condition of the propellant and the ambient temperature;
f) Ammunition that has been projected out of the site may well penetrate the ground surface, thereby leading to a requirement for sub-surface clearance;
g) At the “seat of the initial explosion”, if that can be identified, a crater will have resulted. There are, however, likely to be a multitude of craters after a serious event. It shall be

assumed that ammunition is still contained within the crater, and subsequent explosions may have partially "filled in" craters, thereby in effect burying ammunition;

h) The ammunition that has been involved in the explosion, but did not deflagrate or detonate, will be very susceptible to the weather; risks will increase significantly during lightning storms and further explosive events initiated by lightning strikes may occur;

i) The infrastructure (buildings, roads etc.) is highly likely to be in an unstable condition, and be at risk of collapsing;

j) Subsequent bad weather may have led to flooding and mud slides covering up ammunition and UXO; and

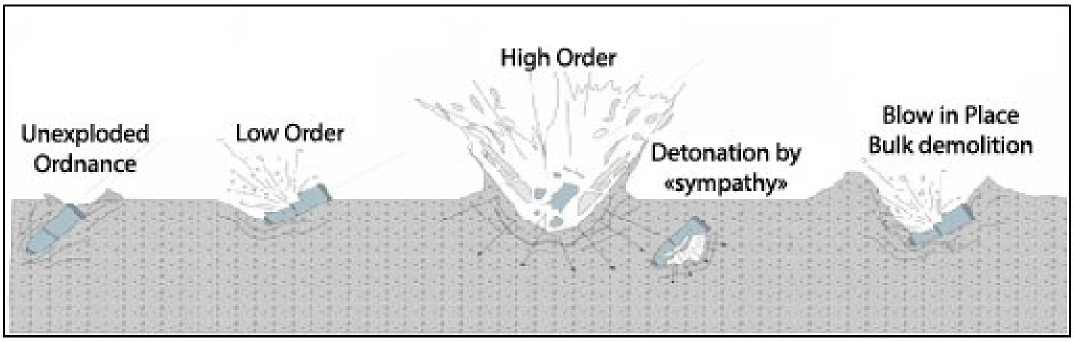
k) Exposed explosives may contaminate surface and subsurface water. This water may be colored pink as the result of TNT, RDX and HMX contamination. Explosives are also toxic; for example, people exposed to TNT over a prolonged period tend to experience anemia and abnormal liver functions. Personal protective equipment (PPE) (face masks and protective gloves) may therefore be required when collecting explosives that have been pulverized during an explosion, as will a thorough clean-down procedure.

This chapter shows the ignorance about the chemical and toxic realities of containers and the contents of ammunition in general.

It is apparent from the above-mentioned standards that the environmental impact of poorly stored, unexploded ordnance - in more or less advanced states of degradation - is not taken into account. The increasing impact of the prolonged presence of ammunition, on or in the ground undergoing all the meteorological constraints – which accentuates the degradation of this ammunition and the transfer of pollutants by rainwater, animal grazing, etc. - is even less so acknowledged.

Mortars taken out of water in Democratic Republic of Congo
© M. Guilbaud

If the explosive contents are open to the environment, the explosive materials, or their residues, can contaminate the ground and water, and can have a substantial effect on the environment. Asbestos, chemicals, and liquid propellants can be found in the missiles. Depleted Uranium (DU) projectiles can also be encountered. DU must be treated in accordance with Technical Note 09.30 20.[11]



Different states of unexploded ordnance – source BRGM http://infoterre.brgm.fr/rapports// - D. Hude

Metal scraps collected during a visual inspection in the Misurata depot– Libya © Marceau Guilbaud

II - Overview

"Environmental impacts are silent"

To mention environmental pollution due to the presence of unexploded ordnance, whether due to an accidental explosion in an ammunition depot - such as in a confirmed hazardous area (ERW) or an improvised explosive device (IED) - may be surprising. Indeed, few people, including EOD technicians and international actors in charge of mine action and Weapons and Ammunition Management (WAM) programs, link the risk of chemical pollution to the presence of conventional unexploded ordnance. As for the donors, they cannot envisage that such a risk could exist with conventional ammunition if they are not informed.

The risk of environmental pollution will be aggravated by the delay of the implementation of a decontamination project with soil remediation. The more time passes, the more the weather conditions will worsen the degradation of ammunition, and the diffusion of polluting molecules in air, water and soil. The food chain will be directly impacted by the transfer of pollutants into the soil and groundwater, which will lead to the concentration of these molecules in the root systems of plants, which will then be consumed by grazing animals, which in turn will be eaten by humans. The transfer of pollutants into the groundwater will affect drinking water used for everyday consumption, water from which the fishery resources is taken will also be affected, etc.

A summary investigation carried out during a 2010 impact survey in Chad by the author identified the deaths of ten pregnant women in two villages close to an uncleared shooting range. These deaths could not be explained by local medicine and were not related to purely medical causes. The author proposed to the regional authority to do an analysis of the water in the wells of these two villages to verify the presence of heavy metals originating from the degradation of unexploded ordnance left on the ground or in the uncleared bullet backstop.

Chemical pollutants from conventional ammunitions

In general, a conventional ammunition is a coherent assembly loaded with an active substance (explosive or pyrotechnic), itself enclosed in a more or less thick envelope, made of metal or another material. The means of initiation can be fixed "on place" to the ammunition, a motor or a propeller may also be physically attached to the body of the ammunition in a permanent manner (ready-to-use).

All active ingredients, casings and internal parts necessary for the coherence of the whole ammunition are compounds of chemical molecules and heavy metals.

Toxicity of active materials from conventional ammunitions

What about the toxicity of explosive materials?
Nitro aromatics (Trinitrotoluene: TNT, DNT and MNT) and nitrates (RDX and HMX) are extremely harmful to health in very small quantities (see below).

The Online Encyclopedia of Occupational Safety and Health from the International Labor Office (ILO)[12], provides full records of the properties of nitro aromatic esters and their impacts on human health.

Due to their molecular structure, explosive compounds are very resistant to destruction. Although the efficiency of the destruction of explosive materials has not been measured during live fire, emission factors however indicate that 10% of the explosive materials are not destroyed and therefore released into the environment.[13]

Impacts related to the delays in dealing with pyrotechnic pollution

“Forgotten" unexploded ordnance on or below the surface or underwater, is a permanent source of pollution due to the diffusion of toxic molecules into the environment. The delay before clearance increases the risk of damage to human beings, fauna and flora.

Since the end of the WWII, States, international organizations, local actors (hunters, fishermen, farmers, foresters, etc.) and environmental NGOs have periodically warned about the seriousness of this risk, but there is still no commonly accepted strategy regarding the impacts of forgotten ammunition, and very large stocks of ammunition dispersed in the environment. Unfortunately, this ammunition is often still active, and can remain active for decades to come, even centuries, when protected from air and corrosion (clay soil for example). The national demining services of the European countries affected update and process a very large amount of ammunition from the two World Wars as well as older ammunition. These still cause death and serious physical injuries to all those who come into contact with them, either accidentally or unconsciously.

What is the situation in developing countries which lack the financial and human resources to assess the level of the problem? The international community must take this problem into account in order to deal with both long-standing and current pollution.

The longer we wait, the greater the environmental impact, without reducing the explosive danger. Environmental impacts are silent while explosive impacts, which are louder, cause death or physical disability while having a significant social impact!

Heavy Metals

"A metal is a material, most often from an ore or another metal, with a particular luster, good conductor of heat and electricity, with characteristics of hardness and malleability, thus combining easily with other elements to form alloys usable in industry, goldsmithing etc. In general, heavy metals are called natural metallic elements, metals or in some cases metalloids (e.g. arsenic) characterized by a high density, greater than 5 grams/cm^{-3}. We find in some old publications the name "heavy metal". Forty-one metals correspond to this general definition to which five metalloids must be added."[14]

In military ammunition, the following heavy metals are encountered either alone or in combination (in bold the most "*at risk**")[15]:

- Aluminum into explosives and/or pyrotechnic filling,
- Ammonia,
- Antimony (added to lead into small-arms cartridges),
- **Arsenic** (added to lead into small-arms cartridges),
- Barium,
- Benzidine,
- Boron,
- **Cadmium**,
- Copper,
- Depleted Uranium,
- Iron oxide,
- **Lead** (bullets, « canister » balls, rotating band)
- **Mercury** (Mercury Fulminate into primers and detonators),
- Molybdenum,
- Nickel,
- Silver, into electronic circuits,
- Strontium,
- Sulfide,
- Titanium,
- Tungsten,
- Zinc, etc.

*Trace metals mainly have an impact on the health of children and pregnant women. Not all of them are toxic, but some, marked in bold in the above list, present a certain toxicity to humans at very low doses, leading in particular to more or less serious neurological damage.[14]

Organics compounds from conventional ammunition

The United States has defined more than 200 hazardous chemicals that can be contained in military munitions. Among these, the US Department of Defense considers 20 that would be the most dangerous due to their wide use and the potential impact on the environment[15]:

- 2-Nitrotoluene,
- 3-Nitrotoluene,
- 4-Nitrotoluene,
- Methyl Nitrite,
- Nitrobenzene,
- Pentarythritoltetranitrate (PETN),
- Perchlorate,
- Trinitrotoluene (TNT),
- 1,2,3-Propannetriol Trinitrate (Nitroglycerin),
- 1,3,5-Trintrobenzene,
- Hexahydro / 1,3,5-Trinitro / Triazine (RDX),
- N,2,4,6-Tetranitro-N-Methylaniline (Tetryl).
- Octahydro / 1,3,5,7-Tetranitro / 1,3,5,7-Tetrazocine (HMX),
- 1,3-Dinitrobenzene,
- 2,4-Diamino / 6-Nitrotoluene,
- 2,4-Dinitrotoluene,
- 2,6 Dinitrotoluene,
- 2,6-Diamino / 4-Nitrotoluene,
- 4-Amino / 2,6-Dinitrotoluene,
- 2-Amino / 4,6-Dinitrotoluene,

To this list, it is necessary to add the following:

- Acetone peroxide (APEX), also known as **triacetone triperoxide (TATP)** or **tri-cyclic acetone peroxide (TCAP)** or **diacetone dideoxide (DADP).**
- Ammonium nitrate, Lead nitrate and Potassium nitrate,
- Ammonium perchlorate,
- Black powder,
- Cellulose acetate,
- Cellulose nitrate,
- Hexachloroethane,
- Lead acid,
- Mercury fulminate,
- Nitrostarch,
- Phosphorus,
- Picric acid,
- Potassium perchlorate,
- Sodium borate,
- Sodium chlorate,
- Sulfide,
- Tetrazene,
- Zinc oxide, etc.

Although research on environmental problems related to chemical pollutants dates back over thirty years, the potential effects in terms of environmental impacts remain largely unknown. The nature of the potential effects and the impact on health depend on the dose, the duration and mode of exposure, the climate as well as on the vulnerability and sensitivity of the populations exposed.[16]

The following gives some health effects for five of the most dangerous compounds.[15]

Explosive	Effects
TNT	Risk of liver and skin; cataract.
RDX	Risk of cancer, prostate and nerve problems, nausea and vomiting. Damage to internal organs observed when tested on animals.
HMX	Potential liver and nervous system damage in animal testing.
Perchlorate	Itching, lacrimation and pain, gastroenteritis, nausea, vomiting and diarrhea. Possibility of tinnitus, dizziness, increased blood pressure, blurred vision and tremors. Impacts on the Thyroid.
White Phosphorous	Reproductive impact, skin burns, throat and lung irritation, vomiting, stomach cramps, liver, heart or kidneys deficiency. Death.

Concentrations of active elements in the environment depend on the type of ammunition, environmental conditions, and ammunition density. Generally, the latter is low and decreases rapidly with distance from the site both in soil (or water) and air. However, transfers to groundwater or to more remote areas can also occur through rainwater, wind and sunlight.

Other components of conventional ammunition

Military conventional ammunition consists, in most cases, of a body, a priming system and a propulsion system. Electrical or electronic means are also components of modern munitions.

Aging and degradation of conventional ammunition

Ammunition has a lifespan defined by the manufacturer during design, and depends on storage conditions and external conditions of use. The envelope of the ammunition is painted, in order to delay the aging effects of the ammunition. In addition, the designer has also created a packaging that will provide the best storage, transportation and handling conditions until its final use, which will normally mark the end of its life. Outside of this optimal situation, the service life of the initial ammunition will be reduced by different factors of degradation of[17]:

- Energetic material (load)
- Electronic parts
- The envelope or other protective mean

Any mechanical damage (impact, corrosion) or vibration accelerates ageing. However, in addition to this damage, the ammunition also degrades chemically over time. Degradation will also be accelerated by:

- large temperature variations (for example, change of hot/cold cycle);
- low temperatures;
- high or low humidity; and/or
- pressure.

Corrosion of conventional ammunition

Corrosion refers to the alteration of a manufactured object by its environment.
The best-known examples are the chemical alterations of metals in an aquatic environment - with or without an oxygen supply - such as rusting of iron and copper, the formation of verdigris on copper and its alloys (bronze, brass). This is known as aqueous corrosion.

Atmospheric corrosion is generated by the atmosphere and its climatic conditions. The examples below show components which have been exposed to climate and/or humidity at an ammunition depot in MISURATA (Libya) after an explosion following a bombing raid.

Broken unfuzed bomb releasing its load. The body suffered the effects of intense heat and projections
source ©M. Guilbaud

Copper artillery primed case. No propelling charge inside. Only stressed on the outside.
source ©M. Guilbaud

Rocket motor with electronic components and solid fuel.
Source ©M. Guilbaud

Burnt cartridges (Lead and antimony).
source ©M. Guilbaud

Projected unexploded ammunition collected during a visual inspection in a depot in Misurata – Libya

© Marceau Guilbaud

III – Health impact

"The expected climate change could exacerbate the risks of flooding of certain CHA or ammunition depots"

Ammunition pollution, in general, is mostly identified with lead contamination. Indeed, this metal is known to cause lead poisoning, regardless of the absorbed dose, and mainly affects pregnant women and children. However, in the recent years, materials with high explosive power have also been involved. Their sanitary effects on the living are often mentioned in English literature, but there are no studies on such effects in French literature.

For many years, military conventional munitions have been manufactured with toxic or ecotoxic compounds, some of which are neither degradable nor biodegradable. Lead, mercury and arsenic are the most common, but more recently, depleted uranium has also been used in anti-armor munitions and then replaced by Tungsten.[15]

Other compounds (TNT, RDX, Perchlorates...) are slowly degradable. They are found in soil or sediments, both terrestrial and aquatic, where they cause toxic effects which can lead to partial or total sterilization of the soil and intoxication of living beings. It should be noted that there is little to no evidence of air pollution by explosives.[29]

Some others (Nitrates, copper, zinc, brass, cadmium, etc.) are less toxic below certain thresholds.

This paper does not deal with chemical munitions, regardless of whether they are in previous or current use.

Environmental issues related to ERW clearance.

The One Health approach[18] defines issues related to the environment, biodiversity and human health. This approach could be integrated into the reduction of armed violence, including mine action.

Over time, explosive remnants of war (ERW) sink naturally into the ground, and vegetation reclaims its rights to landfill sites. This situation causes chemical decomposition of these munitions, the penetration of pollutants into the soil and water, but also their concentration in plants, and/or transmission to wildlife. Then, over time, depending on the agricultural methods (successive ploughing), the munitions resurface.

Furthermore, the explosion of a munition creates a crater in the ground. This corresponds to the impact of the ammunition causing a more or less deep hole depending on the resistance of the ground, the weight of the ammunition, and the height of descent (drop or orb).

During the explosion initiated by the impact, the crater will be enlarged by a size relative to the net explosive quantity (NEQ), and to the type of explosive or filling. The latter elements will cause the tearing of a portion of soil, and its projection into the surrounding environment. Pollutants from the munition are transmitted to that portion of soil, and to the crater itself, ultimately resulting in local pollution.

During a voluntary destruction carried out by an EOD expert in the field, a crater with the same physical and environmental characteristics as above is also formed.

During any explosion of an explosive substance, a projection of dust accompanies both the chock wave and heat effects. The higher the NEQ, the greater the effects. This can lead to the creation of a cloud of projected pollutants and wastes, which will be subject to prevailing winds and weather conditions. Through this cloud, pollutants will travel to areas more or less distant from the explosion site and fall to the ground depending on the weather and their weight.

Knowledge of the history of a site, war events, the fighting that took place on it is important in order to not forget them, nor their associated risks. This enables their treatment in order to remove all the polluting agents due to these past events. Use of local, regional, national and even international archives, geographic sources as well as geophysical surveys - carried out during preparatory studies for road works, construction, etc. – is essential. Popular narratives can also help locate these places.

The climate has been changing for several years and this could exacerbate the risk of flooding. Ammunition depot areas, whether buried or above the ground, could be subject to this type of event but also to more recurrent fires. So-called "war" forests, due to their use or intensive targeting during one or more conflicts, are also subject under the climate change threat. Increased heat and heavy rain will also have a direct impact on the degradation of metals and thus pollution.

In recent years, brand new explosives including liquid or solid rocket fuels, have been discovered in storage sites. Depleted uranium has been used, although it is disputed by nations which have used it in the past on certain sites: Iraq, Balkans, etc. However, it takes time to identify the new elements on the one hand, and to define their toxicity on man and his environment on the other. For example, tungsten has replaced Depleted Uranium for, a priori, reasons of lesser toxicity. Injections of tungsten dust on rats induced cancer with localized tumors on the injection area. No evidence has been found on humans, except in the case of very long-term exposure or ingestion.[19]

Chlorate has been used intensively since WWI (Cheddite, TNT) in composite explosives for its oxidizing qualities, in combination with high-energy fuels. Deemed too sensitive, it has been replaced by the more stable perchlorate. The latter has been widely used in grenades and trench ammunition.[20] In the North of France, the presence of perchlorate in drinking water is a potential risk of developmental delays in children.[21]

Hydrocarbons are also pollutants present in the propulsion engines of missiles manufactured during the Cold War and still found in many theatres of war.

Issues related to types of toxicity

Explosives are stable in the soil and resistant to biodegradation. Different authors have reported that TNT (2,4,6-trinitrotoluene), RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) and HMX (octahydro-1,3,5, 7-tetranitro-1,3,5,7-tetrazocine) are toxic, but investigations have been carried out in artificial soils with isolated substances.[22]

The same component of ammunition (e.g. hexahydro-1,3,5-trinitro-1,3,5-triazine) can be characterized by different types of toxicity.[22] In addition, certain components (especially heavy metals) can mutually reinforce their toxicity (and ecotoxicity) or exacerbate that of other components (so-called synergistic effects and possible potentiating effects). Toxic interactions, which can lead to death, have also been demonstrated for certain organic compounds (explosive charge) of ammunition. This was revealed by tests carried out on laboratory rats.[22]

Examples of toxic or ecotoxic explosives or propellant agents which may be present in the filling of conventional military ammunitions.
Source : GESTIS Database[23]

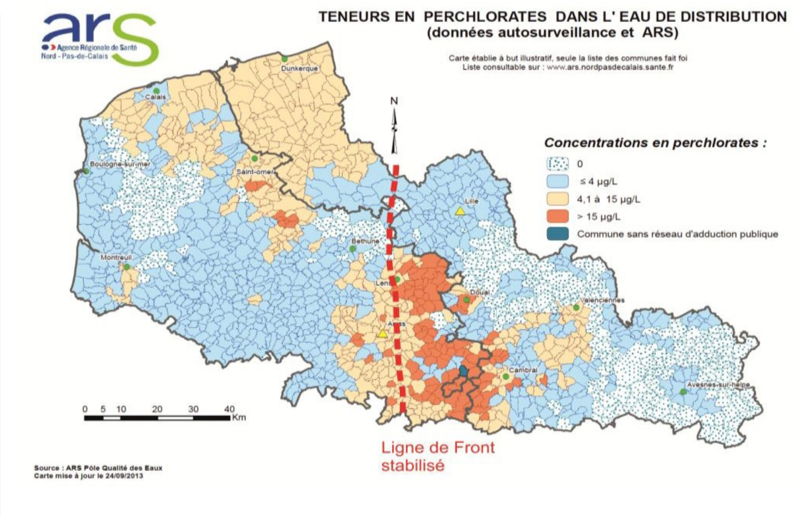
Common name	Chemical name CAS number	Solubility in water (g./l)	Comments
Mercury fulminate	Mercury fulminate (CAS 628-86-4)	Very slightly soluble	Toxic by inhalation, ingestion, contact with the skin: dermatitis or even erythema. Significant toxicity in the aquatic environment with prolonged effects.
Amatol	2,4,6-Trinitrophénol + Ammonium nitrate (CAS 8006-19-7)	Completely soluble	Toxic by inhalation, ingestion, contact with the skin, with the eyes: Corneal damage and

	(CAS 88-89-1) CAS 6484-52-2)		nasal mucus, dermatitis (yellow skin), gastric pain, nervous disorders, blood, renal and liver damage. Damage to fertility, mutagens and carcinogens are likely.
Cordite	Nitrocellulose, Nitroglycerin, Nitroguanidine (CAS 9004-70-0)	Slightly soluble	Insufficient data.
HMX Octogen	Octahydro-1,3,5,7-Tetranitro-1,3,5,7-Tetrazocine (CAS 2691-41-0)	Insoluble	Toxic by ingestion, skin contact.
Lyddite	Picric Acid (CAS 88-89-1)	Slowly soluble	Toxic by inhalation, ingestion, in contact with the skin, with the eyes: Corneal damage and nasal phlegm, dermatitis (yellow skin), gastric pain, nervous disorders, blood, renal and liver damage. Likely mutagenic and carcinogenic effects on fertility.
PETN	Pentaerythritol tetranitrate (CAS 78-11-5)	Slightly soluble	Insufficient data.
RDX Cyclonite Hexogen Hexolite Composition A, B, C, D and H6	Cyclotrimethylenetrinitramine Hexahydro-1,3,5-trinitro-1,3,5-triazine (CAS 121-82-4)	Insoluble	Suspected to be carcinogenic to humans! Insufficient data.
Tetryl	2,4,6-Trinitrophenylmethyl nitramines (CAS 479-45-8)	Very slightly soluble	Tetryl is one of the most toxic and dangerous compounds for human beings.
TNT	2,4,6-Trinitrotoluene (CAS 118-96-7)	Very slightly soluble	Exposure to large doses can cause anemia and liver disease. Enlarged spleen, immune system damage and skin irritation were also observed in animals which had ingested and inhaled trinitrotoluene. Other harmful effects include reduced male fertility and a risk of cancer (TNT is a derivative of an aromatic hydrocarbon, many of whose properties are

			common with benzene, which is carcinogenic in nature).

Examples of toxic or ecotoxic explosives or propellant agents which may be present in conventional military ammunitions.
Source : OMS[24]

Common name	Chemical name CAS number	Solubility in water (g/l)	Comments
Uranium - Depleted Uranium		Insoluble	Toxic by inhalation, ingestion, skin contact. Depleted uranium is both potentially chemo toxic and radiotoxic, with kidneys and lungs being the two organs most affected. The physical and chemical nature of the depleted uranium to which the subject is exposed, as well as the intensity and duration of the exposure, determine the health effects. Long-term studies of professionals exposed to uranium have reported certain impaired renal function depending on the intensity of the exposure. However, there is some evidence that these effects may be transient, and that kidney function may return to normal after the source of excessive exposure has been removed. Insoluble uranium particles, 1 to 10 µm in diameter, tend to remain in the lungs and could cause radiation injury or even malignant tumors in the lungs if their presence results in sufficiently intense radiation over a prolonged period of time.



Example of pollution impact from WWI ammunition
demonstrating the link between the location of combat sites and the presence of Perchlorate pollution.
Source BRGM http://infoterre.brgm.fr/rapports//https://www.researchgate.net/publication/265623100 - D. Hude

Example of issues related to type of toxicity

In the report *Civilian exposure to munitions-specific carcinogens and resulting cancer risks for civilians on the Puerto Rican island of Vieques following military exercises from 1947 to 1998*[25] explains, through the clearance work carried out by the US Army in Puerto Rico (Vieques Island), the civilian population’s risk of contracting a type of cancer as a result of exposure to military activities which involved munitions that were poorly stored and not destroyed early enough.

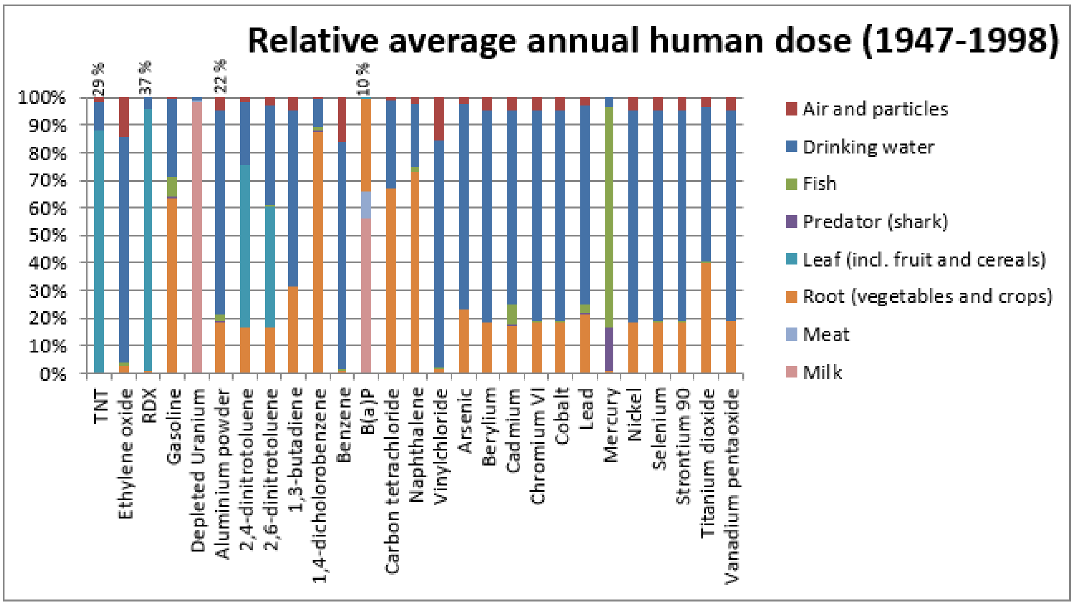


Table defining the modes of absorption (%) of carcinogenic molecules by type of explosive material by the populations of the Puerto Rico Islands[25]

Hand grenades disposal in a tire to contain the projection in the surrounding environment – Mauritania.
© M. Guilbaud

IV – Completed clearance

An explosion in an ammunition depot, due to a mine action operation, an explosive remnants of war (ERW) or any explosive charge placed in an improvised explosive device (IED), could cause partial destruction of the munitions in question.

Ammunition whose body is sufficiently resistant to shock, blast and heat, or too far from the explosion site, will be projected either partially or completely. The same projection can take place if the storage magazine is of the light or open-air type. Depending on its weight, the ammunition will be projected following a more or less taut orbit. In all cases, the ammunition will have suffered from the effects of shock, blast, heat and projection (beginning of initiation) causing partial or total damage to the envelope, exposing the components of the ammunition in its storage position to the open air (see photos below).

« Many ERW have been “lost”, or their disposal sites have been "forgotten" »

In storage, ammunitions are either primed or not. If the fuze is "*on-place*", the safety catch, if any, is in place to prevent inadvertent firing of the ammunition in question.

However, upon impact with the ground or with any other obstacle, the ammunition may undergo ruptures exposing active priming elements (primer, detonator, striker). As a result, the unforeseen ignition may take place during the movement of the ammunition by the technician responsible for the pyrotechnic depollution. The risk is therefore pyrotechnical due to a probable explosion but also environmental due to the exposure of the internal components to the environment and their accelerated degradation.

Some examples of ammunitions that suffered the effects of an explosion

Rupture of the "stand-off" priming device from the shell
Source ©M. Guilbaud

The explosion scattered ammunition components which mixed with rubble. Source ©M. Guilbaud

Rupture of the shell body, exposing the inside load to the environment. Source ©M. Guilbaud

The heat accelerated the degradation of the metallic parts
Source ©M. Guilbaud

Rupture of the propelling device exposing electronic components. source ©M. Guilbaud

Breakdown of external body.
Source ©M. Guilbaud

In the case of thrown, placed or projected ERW (UXO or AXO) and IEDs, the fact that these did not work as expected does not remove the explosive hazard nor the environmental impact. Again, the time taken to carry out mine action interventions is significant.

Reduction of the explosive risk and environmental impact

Although clearance methods are not the main focus of this paper, environmental pollution caused by the lack of clearance of propelled explosive remnants of war must be taken into account. Indeed, these are propelled by a solid or liquid engine which, although in storage position at the time of the explosion of the depot, can take on the speed of propulsion that will move the ammunition in question along a more or less taut trajectory and over a distance of up to several hundred meters or even several kilometers.

Delaying clearance of a confirmed danger zone will result in increased risks and threats. This delay will allow a transfer of pollutants from the decomposition of these munitions under the effect of weather conditions.

In the aquatic environment, decomposition times are faster and therefore the impacts will be more immediate on the fauna and flora; with transfer to the human food chain.

Clearance requirements

The intended use of land that has undergone an accidental or induced explosion, as being polluted by any explosive ordnance as a result of armed activity, must be an essential factor in determining the clearance requirements, as well as for the allocation of resources required. The intended use of land should define the level of pollution control required; for example, it is useless and costly to clean up land to a depth of 2 meters if this land is to be reused to create forest space.

IMAS 09.10[26] defines the following: *" Land shall be accepted as 'cleared' when the demining organisation has ensured the removal and/or destruction of all mine and ERW hazards, (including unexploded sub-munitions), from the specified area to the specified depth”.*

The specified depth of a clearance operation must be determined by a technical survey, or by any other reliable source of information which establishes the depth of burial of the hazard due to the presence of mines or unexploded ordnance, along with an assessment on the intended use of the land. In the absence of verified information on the burial depth, a default depth should be defined by the national authority responsible for mine action. It should be based on technical data concerning the threats usually encountered in the country, while taking into account the intended use of the land. From past experience, the immediate pollution of an explosion will be on the surface or just below the surface. The most common metal detection means are limited and therefore a depth of 130 mm is considered standard.

Clearance methodology

The following factors must be taken into account when developing EOD[26] clearance methodologies:

a) A technical survey must be carried out, covering the following points:
   - Identification of ammunition types and the risks of unexploded ordnance instability;
   - Identification of dangers in depth; and
   - An assessment of the density of unexploded ordnance within the radius of the danger zone (m^2). The density of ERW / ammunition includes;
     1) primed ammunition which had to be destroyed in situ as ERW;
     2) un-primed ammunition that has been removed manually; and
     3) metal fragments from munitions that detonated or exploded.

b) A pollution control plan must be based on a technical evaluation and a risk assessment. It should include:
   - Formal risk assessment;
   - The necessary resources (including heavy and armored lifting devices to create a passage); and
   - Sufficient training.

The time required for EOD remediation is always difficult to assess due to the large number of variables.

Clearance of a CHA following a bombing of a Misurata depot. The method used is referred to as "Battle Area Clearance". The goal is to get no signals during quality control. Misurata – Libya © M. Guilbaud

There are different processes for performing EOD[26] remediation operations:

a) Define the radius of the danger area which requires EOD clearance;
b) Grid that area from the outside to the inside, taking into account the danger area and the ammunition storage area;
c) Within the danger area, in places where the population is exposed to the highest risk, clearance must be undertaken as a priority;
d) Have the marking operations carried out by qualified personnel in ammunition. The latter, unlike EOD personnel can save time, negate the need for on-site destruction and, in some

cases, give recommendations regarding the displacement of ammunition, which EOD personnel are not always qualified to do. Their training in ammunition design means that they can effectively expedite clearance operations within acceptable safety limits.

e) The basic paint marking system should be;
   - GREEN - no explosive charge; can be moved to the waste area by anyone;
   - ORANGE - Certified as "safe to move" by a specialist, for destruction in a bulk demolition pit. The ammunition can be moved by support personnel; and
   - RED – Destroyed on site by EOD personnel during a planned destruction session.

f) Carry out the initial surface clearance, unless the threat assessment has shown that clearance in depth is absolutely necessary and a priority. Any primed, unsecured, or unknown ammunition must be destroyed by detonation or by low order method on place;

g) Establish a demolition zone for the destruction of uncovered munitions that have not been primed or are defined as movable;

h) Establish a waste verification procedure to ensure that all traces of explosives have been removed (Free from Explosive - FFE); and

i) Establish a system for recording ammunition during clearance and destruction operations (it is then possible to compare these figures with those of ammunition losses in the stockpile (in the case of official depots).

The operating methods of a depollution project will depend on all elements previously defined, however it is essential to deal with both pyrotechnic (accidental explosion during the clearance) and environmental risk simultaneously.

One of the best methods will be the system used during the clearance of a battlefield[26]: a line of personnel in charge of the following operations:

- Visual search of the ground surface;
- Removal of all items related to explosive or neutral ammunitions;
- Marking of the excavated lines, as they progress;
- Evacuation of the elements found during the visual search towards the storage area which must be compartmentalized according to their dangerousness and before destruction of the presumed explosive components

The personnel deployed on this line are not EOD technicians but must have received sufficient training before their deployment on site.

An ammunition expert should be positioned behind the visual search line. When a member of the line raises an arm to indicate that he/she has spotted a suspected object, the expert steps forward to that person for diagnosis. This gesture must immediately stop any movement of the line until the team leader gives the order to resume search.

After identification of the risk by the ammunition expert, a colored stake will be placed near the identified object to indicate the type of risk and appropriate action to be taken for the treatment.

During a visual search, the risk below the surface will only be taken into account if there is apparent evidence above the ground. Should the visual search include the risk of pollution buried at a maximum depth of 180 mm, personnel shall be equipped with appropriate metal detection equipment.

Scraps and ammunitions storage areas before bulk demolition

The work philosophy should be as follows:

« Everything in front of you is dangerous while the back is secured ».

In order to reduce risks, if possible, a destruction area should be established nearby and all elements at risk should be destroyed regularly. Thus, storage will remain secure and the transport limited. The waste area should be secured to prevent malicious tampering.

At the end of the depollution operation, the cleared area must be marked as safe, while the untreated area must be identified as hazardous. The danger symbology used must be known to all those who need access to the area in question.

Bulk demolition area

Final marking with stones

Recovery of metallic and concrete scraps before transportation to retreatment site.
Source © M. Guilbaud

V – Soils remediation

The accidental or induced explosion of an ammunition can cause explosive and chemical pollution resulting in a safety and environmental impact. The more time passes before a pyrotechnic depollution is carried out, along with the removal of polluting substances and materials from the soil, the greater the environmental consequences.

The longer the clean-up operations take, the greater the transfer to water, soil and the food chain will be. The type and extent of pollution will therefore have to be defined in order to implement soil remediation measures.

The overall goal of soil remediation is to treat the elements affected by solid, liquid or gaseous pollutants in order to reduce the level of pollution to an acceptable standard allowing a "normal" life, i.e. respecting ecosystems and food needs of living beings on our Earth. To date, soil remediation has been used mainly to reduce the impact of pollution by hydrocarbons and heavy metals. But, with regard to pollutants from ammunition, few operational actions are carried out in the framework of humanitarian mine action. Only certain developed countries have the expertise to do so and the costs are often considered prohibitive[27] with regard to actual physical methods!

The author had noted, in the course of pyrotechnical clearance projects in the Democratic Republic of the Congo, that despite the complete clearance of ERW/mines and related materials, the soils had become sterile and that cultivation was no longer possible.

Recent studies have shown that methods can be deployed at reduced costs with significant efficiency.[28]

"*The choice of the pollution treatment process results from a combination of criteria: the place of treatment (in-situ, ex-situ), the action to be taken (stabilization, extraction or degradation) and the technique to be implemented work to achieve it (mechanical, chemical or biological). These three parameters are extremely linked to the nature of the reconversion of the site. In fact, the levels of depollution required will not be the same if the site is planned to be, for example, transformed into a parking lot or a residential area within this case a human activity potentially in contact with the ground.* "[29]

Professionals in remediation of soil polluted by explosive ordnance have different methods: incineration, stripping, etc. These are very expensive per hectare and require a second treatment operation on an outdoor site before bringing the soil back after treatment, or a complete replacement of the initial soil. In addition, the so-called physico-chemical treatment generates waste and/or greenhouse gases. Stripping off the top layer of soil to be remediated leads to soil destructuration and erosion. Finally, this treatment reduces the biological activity of the initial soil: the remediated land, or the land that would be put in place as a replacement, no longer contains the essential nutrients for the local vegetation.

More recent soil remediation methods use biology. Indeed, plants and/or micro-organisms are tested to remediate soils polluted by heavy metals as well as chemical molecules from explosives.

As of the date of this paper, laboratory tests or tests on experimental sites are being carried out mainly in the United States. No wide-area operational deployments, according to criteria defined by the international humanitarian mine action community, in developing or emerging countries have been carried out.

The use of micro-organisms "*would be effective in degrading organic pollutants but the implementation of pollution control requires significant technical means. In the same way as for physicochemical methods, the implementation of these bio-depollution methods requires the excavation of soils and their treatment in bioreactors or in composting areas.*" [27]

For a few years, plants have also been used to remedy soils, inland waters and groundwater polluted by heavy metals and/or explosive compounds. In fact, plants have demonstrated their direct or indirect actions on pollutants by absorbing or degrading them. Other plants store pollutants in their roots, rhizomes, stems and leaves. These actions are designated by a general term: phytoremediation, and with regards to explosive compounds, could be defined as phyto-clearance.

We will also talk about myco-remediation or myco-depollution by using fungi to remedy ecosystems.

In the context of phyto-depollution we will talk about:

- phytoextraction,

- phytostabilization,
- phytodegradation or Rhizodegradation,
- phytotransformation, and
- rhizofiltration.

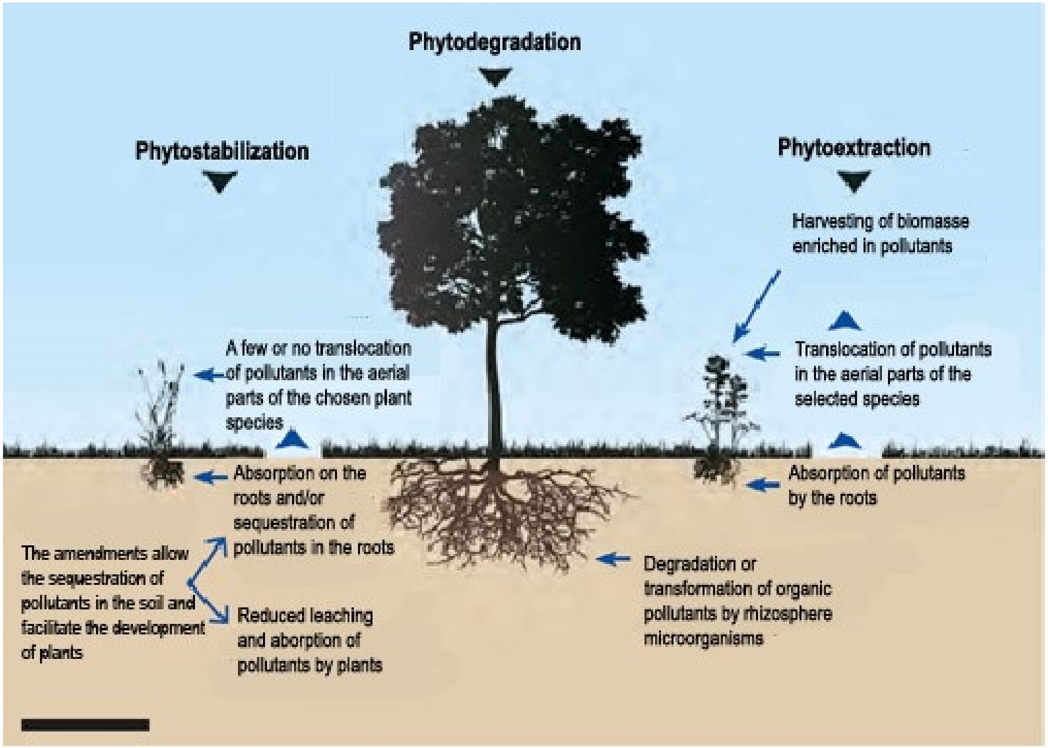
Phytovolatilization appeared recently to treat pollution by mercury or selenium.[30]

Phytoremediation and Phyto-clearance techniques

> The dictionary defines phytoremediation as *"a process of decontaminating soil or water by using plants and trees to absorb or break down pollutants."*

The term "*phyto-clearance*" could be defined as "*the clearance of soil or water, polluted by explosive compounds, by using the metabolic activity of plants.*"

Plants can either filter, store or even transform pollutants made up of heavy metals but also explosive compounds.

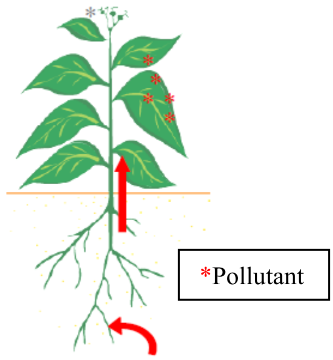


Pollution management techniques – Phytotechnologies applied to polluted sites and soils – INERIS – November 2018[31]

Phytoextraction (phytoaccumulation/phyto-filtration)

This method is based on the use of hyperaccumulating plant species which absorb from the soil, thanks to their root systems, pollutants, and transport them in their aerial parts (leaves)[32], allowing a reduction of the concentrations of pollutants in the soil. Chelators[33] can be added to improve the natural capacities of plants[34].

This method proves effective for a wide variety of heavy metals but remains limited because only the pollutants which can be assimilated by plants are "treated". The possibility of recycling these metals (phytomining) would make this technique more profitable[35] and avoid the incineration or composting of "*loaded*" plants.

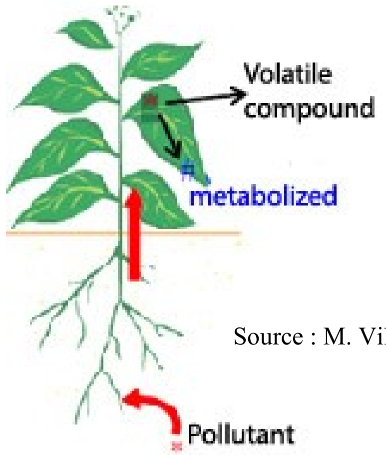


Source : M. Villa[29]

Phytodegradation or Phytotransformation

This method is based on the capacity of certain plants to absorb a pollutant and to degrade it. Animals can also have this ability naturally but, while they reject these digested residues by excretion, plants can completely degrade the pollutant to obtain a fertilizer favorable to their growth.

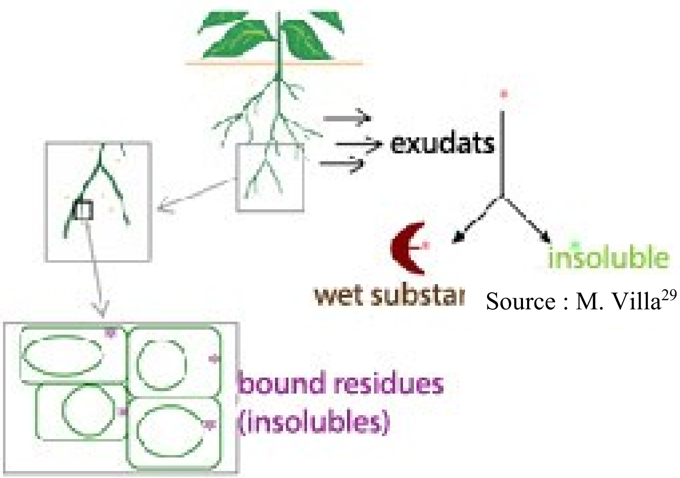
If not consumed, plants will store pollutants in their cells. In animals and humans, insoluble or poorly soluble foreign organisms are mainly transformed by the liver into soluble compounds.



Source : M. Villa[29]

Phytostabilisation

Phytostabilization provides an alternative to the problem of contamination control for pollutants which are not treated in the previous methods.



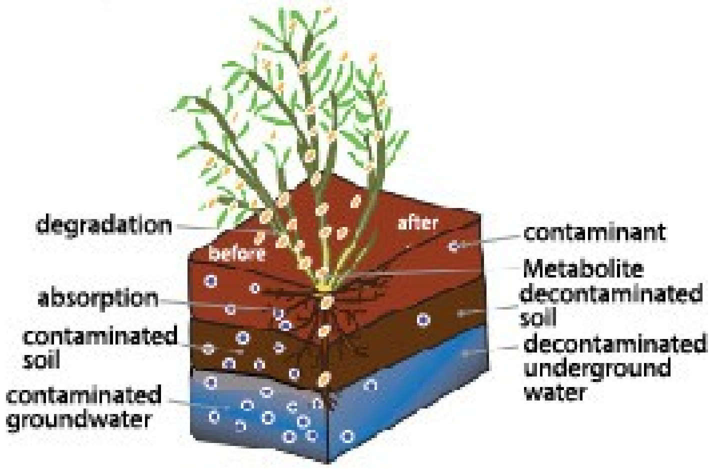
Source : M. Villa[29]

It is based on the storage of pollutants in order to limit dispersion in the environment.

Plants can also be used as organic pumps to absorb large volumes of water. Although the pollutant does not enter the plant, it remains localized in the initially polluted area. This does not reduce pollution in the soil but contains the migration of contaminants to the groundwater.

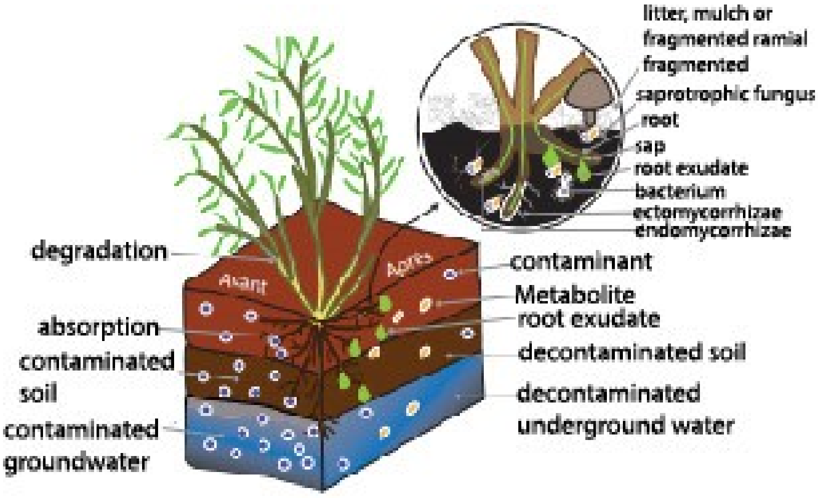
Phytodegradation or Phytotransformation

In this case, the plants absorb and degrade pollutants in their tissues or secrete enzymes relative to the rhizomes and its environment (rhizosphere).



Phytodégradation. source[34]

Rhizodegradation or phytostimulation

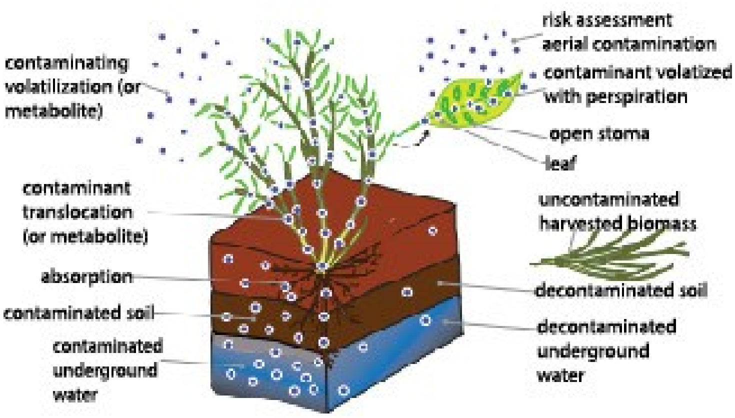


Rhizodégradation. source[34]

This method exploits the stimulating effect of the rhizosphere on the microbiological degradation of organic compounds.[36]

This approach has been used for several years by the US army in the context of the clearance of sites contaminated by explosives (TNT) or by herbicides.

Phytovolatization



Phytovolatisation. source[34]

Organic pollutants, as well as certain inorganic compounds, are extracted from the soil by plants, transported through their vascular system, then released back into the atmosphere by perspiration. This is an interesting technology because the pollutants are thus completely volatilized (in the form of gas), and there is therefore no need to harvest and treat the plants used. On the other hand, the risk of the transfer of pollutants to the atmosphere must be clearly identified before undertaking Phytovolatization. Hybrid poplar can for example volatilize and rapidly degrade TCE present in polluted water.[37]

Bioremediation

Bioremediation techniques use the depolluting properties of microorganisms (mainly bacteria, but also fungi) endogenous or exogenous to the contaminated soil[38] with the aim of degrading or transforming the contaminants to a less contaminated form.[39]

Some of these techniques include the following:[40]

- Bio-pollution;
- Biotransformation;
- Bioremediation;
- Bioaugmentation;
- Biostimulation;
- Bioventilation;
- Composting; and
- Landfarming.

In 2009, an intellectual patent was filed[41] concerning plants capable of absorbing explosive nitro components which are put in culture and then are exposed to anaerobic microbes in the rumen of a ruminant animal. These anaerobic ruminal microbes break down biodegradable components and make them substantially non-toxic to the animal within a few days.

Criteria for choosing plants for phytodepollution

As early as the 16th Century, plants growing in soils rather rich in metals were discovered. Studies in the 19th Century found that this plant - Alyssum bertolonii[42] or Brassica juncea (brown Mustard)[43] - was able to accumulate a high concentration of metals (nickel) from the soil where it grew. Other plants with the same characteristics have also been discovered. It was not until 1970 that this capacity was considered as a means used for soil remediation.

A plant is said to be hyperaccumulating depending on its metal concentration: more than 1.000 mg/g of dry matter in the leaves for nickel, more than 10.000 mg/g for zinc. To evaluate this hyperaccumulation, the transfer coefficient is defined by:

$$\frac{\textit{Concentration of metal contained in the aerial tissues of the plant}}{\textit{Concentration of metal in the soil}}$$

The higher this coefficient, the greater the accumulation of metals.

Three types of behavior have been identified in environments containing heavy metals:[43]

- Low extraction of metals. The plant would control their non-absorption at the root level. There is a maximum tolerance value beyond which the plant dies.
- The extraction is proportional to the quantity of metals present in the soil. The plant is then qualified as an 'indicator' since it reflects the concentration of metal present in the soil.
- The hyperaccumulation of metals in the aerial parts of the plant. The absorption mechanisms are active.

Metal	Lowest Limit (% leaf dry matter)	Number of species	Number of families
Cadmium	> 0,01	1	1
Cobalt	> 0,1	28	11
Copper	> 0,1	37	15
Lead	> 0,1	14	6
Manganese	> 1,0	9	5
Nickel	> 0,1	317	37
Zinc	> 1,0	11	5
Thallium	> 0,1	2	1

Table showing the number of families and species affected by hyperaccumulation[15]

Phytodepollution of RDX and TNT

The current contamination of soil and runoff water by RDX and TNT is widespread and represents a global ecological problem which began as a result of intense military activity during WWI. The environmental hazard assessment from RDX and TNT determined that contaminated soils often contained mixtures of energetic compounds rather than a single explosive. Other contaminants may include nitro esters (nitroglycerin, nitrocellulose), co-products and synthesis intermediates, and products resulting from partial microbial degradation in the soil.[29]

Explosive	Deep Waters (µg/L)	Surface Waters (µg/L)	Sediments (mg/kg)	Soil (mg/kg)
TNT	0,4-21 960	1-3 375	6,7-711 000	0,08-87 000
RDX	0,5-36 000	2,6-224	1-43 000	0,7-74 000

Explosive contamination levels found on military sites[44]

In the case of explosives, phyto-clearance seems to be an appropriate alternative to overcome the shortcomings of the other methods. It can also be used in addition to more conventional methods. Preliminary phyto-clearance studies of RDX and TNT have shown that plants are capable of absorbing and metabolizing these two explosives.

Poplar[45] is commonly used in the United States to treat areas polluted by RDX and/or TNT. Particular attention must be paid to the fall of leaves loaded with pollutants which would return to the ground if these are not collected and destroyed. Burning the leaves would not completely eliminate the RDX, which will then pass from the ground to the air! As the TNT remains in the root system, it will be necessary to pull out the tree and its roots concentrating the pollutant.

Agronomic plants all have different absorption and transfer mechanisms. For pollution in a humid environment, rice will be used. Wheat, corn and soy have been tested for RDX. Wheat will be preferred because its higher absorption capacity (174 kg/ha) followed (in order) by soy, corn and rice. For TNT, corn will be preferred.[36]

Lacustrine plants were tested with 500 and 1000mg/kg of RDX concentration: the bulrush (Typha latifolia), the lakeshore bulrush (Scirpus lacustris), the yellow iris (Iris pseudoacorus), the reed canary grass (Phalaris arundinacea), common reed (Phragmites communis) and sedge (Carex riparia). These plants have the ability to grow in conditions similar to those found in contaminated lagoons.[36]

In order to overcome the limitations of wild or naturally cultivated plants, some have been genetically modified to improve phytoremediation.

Benefits and weaknesses of phytodepollution

The CEA[46] defines in a simple way the benefits and drawbacks of soil phytoremediation as follows:

Benefits:

- Low treatment costs (10 to 100 times lower than conventional technologies);
- Adaptation to large contaminated areas (tens of hectares);
- Pollutant recovery;
- Possible conversion of biomass into energy;
- Visually attractive technology;
- Low disturbance of the contaminated environment;
- Green technology with a good public image.

Drawbacks:

- Limitation to areas colonizable by roots;
- Very long treatment time (minimum 3 years);
- Dependence on the nature of the soil, weather, insect attacks, micro-organisms, etc.;
- Need for large areas and shallow pollution (from 50 cm to 3 m);
- Application to moderate contamination so that the plant survives.

Conclusion

Treating an area polluted by explosive ordnance following an accident at an ammunition depot, involving Explosive Remnants of War (ERW) in a confirmed hazardous area (CHA) or an improvised explosive device (IED), are specific EOD activities. In fact, the ammunition which is initially stored in the safety position is not armed even if the priming systems are "on-place" because the presence of the safety catch prevents a "normal" and intentional firing. However, ERW and/or IEDs are generally primed and sometimes armed (except abandoned ammunition which will only be primed).

The explosion generates an effect of heat, blast, overpressure and the projection of primary and secondary fragments, as well as of ammunition which had not exploded immediately as a result of the explosion. The stored ammunition that suffers from these effects will be thrown inside and/or outside the storage facility. At the end of projection, the ammunition hits the ground or a more or less hard surface, causing partial or total rupture of both the external envelopes and the internal components. This increases the sensitivity of the unexploded active ingredients and the safety mechanisms. In the case of ERW, this consists of ammunition which has been placed, launched or thrown or even fired and which should have operated according to a process originally intended by the designer and user. In the case of IEDs, the munitions typically originated from stockpiles or ERW.

As explained in this white paper, ammunition is a combination of chemical compounds and heavy metals. The effects of the explosion, and/or the action of the environment on the ERW and IEDs will accelerate their degradation. This will produce microscopic elements which will be exposed to the weather conditions of the site. Sun and wind, the projections of sand (in desert areas) will alter the metals, and rain or floods will enable these chemical pollutants to penetrate the soil.

Over time, pollutants will render soils sterile, and will concentrate on plants through their root and/or leaf and aerial systems. This pollution generates a cycle of contamination: animals feed on contaminated plants and waters, and human beings consume meat from the contaminated animals, including the fish living in polluted waters; which ultimately results in the contamination of the whole environment. The sanitary impacts of such phenomena are covered in this report.

All these elements militate in favor of dealing, as quickly as possible, with any pollution by explosive ordnance, regardless of its origin, in order to reduce the pyrotechnic and environmental impacts.

The aim of depollution must be to eliminate the risk of an unexpected explosion, fatal to living beings and facilities but should not conceal the environmental risk. The reduction of the latter must be achieved through the complete removal of pollutants, either physically or using phytodepollution methods.

Another problem can be identified during the on-site demolition of ammunition (blow-in-place). Indeed, other than the financial cost related to the purchase of explosive material for destruction, the safety criteria related to transport and storage as well as to use, must be considered. On-site destruction must be limited to non-removable dangerous ammunition. In most situations, mine action organizations should encourage bulk demolition, on dedicated sites that could be remedied at the end of their use, or after a period of time fixed by contract by the national authority.

Finally, technological equipment makes it possible to detect the presence heavy metals or explosive molecules in the soil, air and water. They should be included in calls for projects accompanied by Standard Operating Procedures to explain their use in the context of remediation of the pyrotechnically depolluted environment.
It would also be desirable to take into account the burning of cartridges for small arms and light weapons, like that of firearms. Cartridges are also generators of chemical soil pollution, especially when burning firearms. Combustion never destroys the pollutants that are released into the air, soil and water along with all associated environmental impacts.

References

[1] http://www.smallarmssurvey.org/weapons-and-markets/stockpiles/unplanned-explosions-at-munitions-sites.html
[2] http://www.smallarmssurvey.org/weapons-and-markets/stockpiles/unplanned-explosions-at-munitions-sites.html
[3] Remediation of Explosives Contaminated Soils at Joliet Army Ammunition Plant via Windrow Composting. https://www.researchgate.net/publication/265623100
[4] https://www.un.org/ga/search/view_doc.asp?symbol=A/70/L.1&Lang=E
[5] https://www.un.org/sustainabledevelopment/en/
[6] https://www.iso.org/files/live/sites/isoorg/files/archive/pdf/en/theiso14000family_2009.pdf
[7] IMAS 07.13. https://www.mineactionstandards.org
[8] IMAS 04.10. https://www.mineactionstandards.org
[9] IMAS 07.13. https://www.mineactionstandards.org
[10] IATG 11.30. https://www.un.org/disarmament/un-saferguard/guide-lines/
[11] TN 09.30.02. https://www.mineactionstandards.org
[12] http://www.ilocis.org/documents/chpt104e.htm
[13] https://www.atsdr.cdc.gov - https://doi.org/10.1080/23779497.2017.1369358
[14] https://www.senat.fr/rap/l00-261/l00-26150.html#fn25
[15] https://sites.google.com/site/tpeexplosifsmilitaires/
[16] Phillips, L., & Perry, B. (2002). Assessment of potential environmental health risks of residues of high-explosive munitions on military test ranges – Comparison in a humid and arid climate. Fed Fac Env J Spring, 7–25. doi:10.1002/ffej.10021
[17] IATG 07.20 – Surveillance et épreuve des munitions en service. https://s3.amazonaws.com/unoda-web/wp-content/uploads/2019/05/IATG-07.20-Surveillance-and-In-Service-Proof-V.2.pdf
[18] https://www.who.int/features/qa/one-health/fr/
[19] https://documentation.ehesp.fr/memoires/2004/igs_ase/05-tungstene.pdf
[20] https://solidarites-sante.gouv.fr/IMG/pdf/sujet_2016_t3s_partie_2.pdf
[21] http://www.journaldelenvironnement.net/article/les-ions-perchlorate-un-danger-pour-les-enfants,50637
[22] http://next.owlapps.net/owlapps_apps/articles?id=1080352
[23] http://gestis.itrust.de/nxt/gateway.dll/gestis_en/000000.xml?f=templates&fn=default.htm&vid=gestiseng:
[24] https://www.who.int/ionizing_radiation/pub_meet/en/DU_French.pdf?ua=1
[25] Sanderson, H., Fauser, P., Stauber, R., Christensen, J., Løfstrøm, P., & Becker, T. (2017). Civilian exposure to munitions-specific carcinogens and resulting cancer risks for civilians on the Puerto Rican island of Vieques following military exercises from 1947 to 1998. *Global Security: Health, Science And Policy*, *2*(1), 39-60. https://www.tandfonline.com/doi/full/10.1080/23779497.2017.1369358
[26] IMAS 09.10 et 09.11. https://www.mineactionstandards.org
[27] United States Environmental Protection Agency. www.epa.gov. Hazardous Substance Superfund avec un budget de 1,074 million de US$ en 2019. Soit 17,5% du budget annuel de protection de l'environnement.
[28] Nitro-based explosive remediation. Propriété intellectuelle 20110052537 - A. Morrie Craig (Corvallis, OR, US) Karen Walker (Philomath, OR, US) Sudeep Perumbakkam (Corvallis, OR, US) Jennifer Duringer (Brownsville, OR, US) Marthah Delorme (Corvallis, OR, US) – 2011
[29] Mireille VILA - Utilisation de plantes agronomiques et lacustres dans la dépollution des sols contaminés par le RDX et le TNT : approches en laboratoire – Thèse soutenue le 15 décembre 2006
[30] https://www.researchgate.net/publication/314087981 Les techniques de depollution des sols contamines par les metaux lourds
[31] https://www.ineris.fr/sites/ineris.fr/files/contribution/Dossiers/INERIS_Dossier%20Phyto_BDder.pdf
[32] S.P.McGrath. In: R.R. Brooks (Eds.). CABI Publishing, Wallingford (1998)
[33] https://www.doctissimo.fr/sante/dictionnaire-medical/agent-chelateur
[34] http://www.phytotechno.com/wp-content/uploads/2018/04/fiches-Phytoremediation.pdf

[35] M. Leblanc, D. Petit, A. Deram, B.H. Robinson, R.R. Brooks. Economic Geology, 94, 109 114 (1999)
[36] I. Kuiper, E.L. Lagendijk, G.V. Bloemberg, B.J.J. Lugtenberg. Molecular Plant-Microbe Interactions, 17, 6-15 (2004)
[37] Newman, L. A.; Strand, S. E.; Choe, N.; Duffy, J.; Ekuan, G.; Ruszaj, M.; Shurtleff, B. B.; Wilmoth, J.; Heilman, P.; Gordon, M. P., Uptake and biotransformation of trichloroethylene by hybrid poplars. Environmental Science & Technology 1997
[38] R. Boopathy. International Biodeterioration and Biodegradation, 46, 29-36 (2000)
[39] M. Vidali. Pure and Applied Chemistry, 73, 1163-1172 (2001).
[40] http://www.pierre-armand-roger.fr/publications/pdf/198_bioremed.pdf
[41] https://patentscope.wipo.int/search/en/detail.jsf? docId =WO2009026184
[42] https://academic.oup.com/jxb/article/52/365/2291/543836
[43] https://sites.google.com/site/tpesurlaphy-toremediation/La-depollution-des-metaux-lourds
[44] Nitroaromatic Munition Compounds: Environmental Effects and Screening Values. Sylvia S. Talmage, Dennis M. Opresko, Christopher J. Maxwell, Christopher J. E. Welsh, F. Michael Cretella, Patricia H. Reno, F. Bernard Daniel, https://link.springer.com/chapter/10.1007/978-1-4757-6427-7_1
[45] Projet BIOFILTREE de l'ADEME. Site INERIS.fr
[46] http://www.cea.fr/multimedia/Documents/infographies/posters/defis-du-CEA-infograhie-phytoremediation.pdf

Legends images/diagrams
Pages 12 et 25 – BRGM -
http://infoterre.brgm.fr/rapports//https://www.researchgate.net/publication/265623100 - D. Hude

Other References

- 2,4,6-Trinitrotoluene transformation using Spinacia aleracea. C.P. Richardson and E. Bonnati.
- ADEME – Les phytotechnologies appliquées aux sites et sols pollués - https://www.ineris.fr/sites/ineris.fr/files/contribution/Documents/phytotechnologies-ademe-2013-1463054029.pdf
- Biodegradation of nitroaromatic compounds. **https://pdfs.semanticscholar.org/01f9/7f4e5a99b91667d5385ba96edb193f1e5e24.pdf**
- Biological remediation of explosive residues - https://link.springer.com/book/10.1007%2F978-3-319-01083-0
- Bioremediation of explosives – Contaminated soils : a status review - https://www.sciencedirect.com/science/article/pii/S0964830500000512
- Defense Explosives Safety Regulation 6055.09 Edition 1 ~ DESR 6055.09, Edition 1 ~ January 13, 2019. https://www.denix.osd.mil/ddes/home/home-documents/desr-6055-09-edition-1/
- Defense R&D Canada – Evaluation of heavy metals contamination at CFAD Dundum resulting from SALW incineration - https://apps.dtic.mil/dtic/tr/fulltext/u2/a396586.pdf
- Environment handbook for Defence materiel - https://infostore.saiglobal.com/en-us/Standards/DEFSTAN-00-035-PT4-5-2018-2018-369772_SAIG_DEFSTAN_DEFSTAN_842340/
- EPA – Phytoremediation resource guide - https://www.epa.gov/sites/production/files/2015-04/documents/phytoresgude.pdf
- Estimates for explosives residue from the detonation of army munitions – https://apps.dtic.mil/dtic/tr/fulltext/u2/a417513.pdf
- FRTR - Remediation technologies screening matrix and reference guide, V4.0 - https://frtr.gov/matrix2/section2/2_10_2.html

- Handbook on the Management of Munitions Response Actions – EPA-505-B-01-001 – 2005. https://www.epa.gov/sites/production/files/2015-05/documents/9530610.pdf
- Handbook on the management of ordnance and explosives at closed, transferring, and transferred ranges and other sites - https://www.epa.gov/sites/production/files/documents/ifuxoctthandbook.pdf
- Journal of environment management – Phytoremediation of explosives (TNT, RDX, HMX) by wild-type and transgenic plants - https://www.sciencedirect.com/science/article/pii/S0301479712004240?via%3Dihub
- Phytoremediation of Lead contaminated soils using vetiver grass - https://jels.ub.ac.id/index.php/jels/article/view/260/296
- Phytoremediation of toxic aromatic pollutants from soil - https://link.springer.com/article/10.1007/s00253-003-1425-1
- Remediation of explosives contaminated soils at Joliet Army Ammunition Plant via windrow composting - https://pdfs.semanticscholar.org/f03d/7eacc11c92e776f27bb899ce777c668e4fbe.pdf
- SW-846 Method 8330B – Nitroaromatics, Nitramines, and Nitrate Esters by high performance liquid chromatography (HPLC) - https://www.epa.gov/esam/epa-method-8330b-sw-846-nitroaromatics-nitramines-and-nitrate-esters-high-performance-liquid
- Technical guidance for military munitions response actions – EM 200.1.15 – 2015. https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_200-1-15.pdf
- Weathering of Lead bullets and their environmental effects at outdoor shooting ranges - https://www.ncbi.nlm.nih.gov/pubmed/12708676