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The endless war: the long-term impact on health and environment of armed conflicts

Matteo Guidotti[1,*], *Andrea Leisewitz*[2], *Massimo C. Ranghieri*[1]

[1]CNR-SCITEC, Istituto di Scienze e Tecnologie Chimiche "Giulio Natta", Milano, Italy;
[2]Integridad, Seguridad y Ética de la Investigación, Universidad San Sebastián, Santiago, Chile
*Benedictine Academician

Abstract

The impact of present and past wars on the environment is significant and multifaceted. Direct effects of warfare include contamination of air, water and soil as well as damages to infrastructure. On the other hand, indirect effects on ecosystems include long-lasting detrimental impacts on natural resources, agriculture, forests, wildlife and, eventually, human life quality. The psychological effects of war on populations can also have indirect negative effects on the environment. It is therefore important to recognize the impact of military operations on the environment and to take steps to prevent or, at least, mitigate these effects, investing in environmental protection and conservation efforts, identifying deliberate crimes against the environment as well as promoting peace and conflict resolution. In times where being responsible and being accountable of our actions is an unavoidable duty, international rules are required to safeguard the environment during and after armed conflicts and to consider environmental crimes as relevant as crimes against humankind.

Keywords

Contamination, War, Pollution, Long-term effects, Conventional and unconventional weapons.

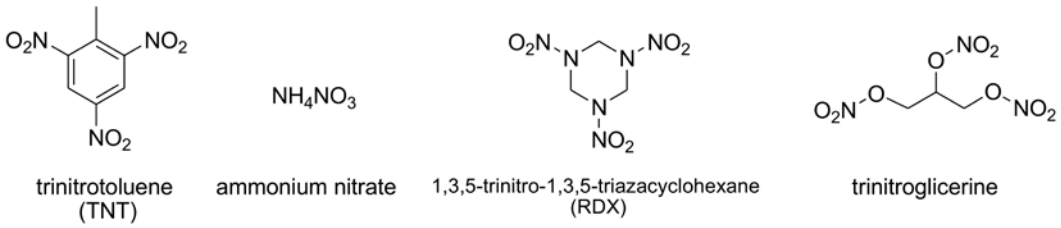
1. Introduction

The impact of present and past wars on the environment and local ecosystems has been a topic of concern since the early 20th century. The effects of armed conflicts on the environment can be both direct and indirect and can have long-lasting consequences, especially since the rise of modern warfare. In fact, starting from the times of World War I, modern combats saw the massive use of an ever-growing variety of conventional or unconventional weapons, of motor vehicles on the ground, at sea and in the skies and, particularly, the enlargement of military actions from well-defined battlefields to industrial and civil urban areas.

Direct effects of war on the environment include damage to infrastructure, contamination of air, water and soil as well as destruction of wildlife habitats [1]. On the other hand, indirect effects of war include forced displacement of populations, diversion of resources and violation of international agreements and human rights. Nevertheless, long-term effects on health and ecosystems, appearing years or also decades after the end of a conflict, are often underestimated or even neglected.

One of the most significant direct effects of war on the environment is linked to the remarkable release of hazardous chemical contaminants in the atmosphere, waterbodies and soil of the areas surrounding the combat area. This can occur as a result of the use of weapons such as bombs, bullets, artillery shells and missiles, which release toxic organic compounds and heavy metals into the environment [2]. Nitrogen-containing explosives, mostly, nitroaromatics and nitroaliphatic compounds, and propellants for projectiles and missiles (highly corrosive, toxic and cancerogenic hydrazine is one of the most common components in propellant mixtures) are recalcitrant pollutants which are often found in high concentrations in combat grounds and whose contamination can last over years (Scheme 1) [3].

Scheme 1. Classical nitrogen-containing explosives.



Likewise, perchlorate inorganic salts, largely used in pyrotechnic formulations and in explosive mixtures and rocket fuels, have been classified as endocrine disruptor compounds and cause detrimental toxic effects to thyroid [4] In terms of unconventional weapons, the use of chemical weapons, such as organosulfur- or amine-based blister agents and phosphorus-based anticholinergic nerve agents, can also have devastating effects on the environment and human health. Exposure even to non-lethal concentration of chemical weapons can cause long-term health effects on target population, such as cancer, birth defects and neurological disorders [5].

Another direct effect of war on the environment is damage to infrastructure. This can include damage to buildings, roads, bridges, industrial plants, production sites and other critical infrastructure, which can have long-lasting effects on the environment and human health. For example, the destruction of water treatment plants and sewage systems can lead to the contamination of water sources, which can cause the spread of waterborne diseases. The damage to infrastructure can also lead to the displacement of populations, which can have indirect effects on the environment.

The indirect effects of war on the environment can be just as significant as the direct effects. One of the most significant indirect effects of war on the environment is forced displacement of populations [6]. This can occur as a result of the destruction of homes and infrastructure, as well as the threat of violence. Displaced populations often seek refuge in areas that are not equipped to handle large numbers of people, which can lead to overcrowding and strain on resources. This can lead to the depletion of natural resources, such as water, food for population and feed for animals, which can have long-lasting effects on the environment. Likewise, during times of war, resources are often diverted from environmental protection and conservation efforts to support military operations [7]. This can lead to a lack of investment in these fields, causing destruction of wildlife habitats, disruption of environmentally friendly industrial protocols and fewer controls on safety good practices in production sites. All this can have long-term effects on workers' health as well as on biodiversity and ecosystems of the affected areas [8].

Last, but not least, war has dramatic psychological effects on populations, which can also have indirect effects on the environment, since damages caused by war, the sense of constant fear and uncertainty and focusing only on survival can lead to post-traumatic stress disorder, depression, anxiety, dissociation (a mental state in which individuals feel detached from their surroundings or themselves) and other mental health issues. This can, on its turn, lead to a lack of motivation to engage in environmental protection and conservation efforts [9].

2. Explosive remnants of war

The most evident and immediate problem connected to soil and marine pollution in areas that suffered from an armed conflict is the impressive amount of unexploded ordnance, typically spread as landmines on the ground, unexploded munitions underwater and contained in shipwrecks off the coast. Unexploded ordnance are explosive weapons (bombs, shells, grenades, land mines, naval mines, cluster munitions, etc.) that still pose risks of accidental detonation, sometimes several decades after they were used or discarded. Such explosive remnants do not necessarily originate from wars. Military training grounds or obsolete dumping sites can also hide an unknown but significative number of unexploded devices, even after the area has been abandoned [10].

Unexploded ordnance from World War I and II are a two-fold hazard. Indeed, over the years the detonator and main charge deteriorate, frequently making these systems more sensitive to disturbance and therefore extremely dangerous to manage. There are countless examples of people coming across old, unexploded devices, often with fatal results. However, even when the ordnance is too obsolete and cannot be triggered anymore, there is still a specific risk of

contamination of soil and underground water, due to release of hazardous organic and inorganic chemicals by the corroded and deteriorated weapons. Lead, mercury, copper, arsenic are heavy metals contained in large amounts in conventional bullets and artillery shells, which can enter the ecosystem through leaching favoured by water and the complexation action by humic acids and then contaminate underground aquifers and fertile soils [11].

Political decisions and policies can also influence the level of risk presented by residual weapons, with abandoned unexploded air-dropped weapons presenting a lower risk than active weapons [12].

3. World War I and the Red Zone in Northern France

World War I led to the development and use on the field of several types of weapons that continue to have an impact long after the war had ended. Moreover, some regions in Europe, where the most intense battles took place, are among the places in the world hit by the highest number of projectiles per unit of surface and they are still paying a heavy toll in terms of ground contamination by toxic organics and heavy metals. One of the lasting legacies of this devastating conflict is the creation of the so-called "Red Zone", a totally forbidden area for the environmentally devastated battlefields of 1914-1918 in northeastern France. These areas, covering over 1200 km^2, were deemed too damaged to support human habitation and were left to return to nature. The Red Zone was established by the French government shortly after the end of WWI. This designation was given to areas that were completely devastated, with damage to properties and agriculture reaching 100% and human life was considered impossible in these regions, around Lille, Cambrai, Soisson and Nancy, close to the Belgian border. The destruction caused by the war left behind a landscape scarred by trenches, craters and ruins, with the soil heavily polluted by various hazardous substances. The impressive environment in the Red Zone is characterized by the presence of unexploded ordnance, extremely high chemical contamination and the remains of human and animal casualties. The area is saturated with unexploded shells, including gas shells, grenades and rusty ammunition. Additionally, the soil has been polluted by heavy metals, chlorinated organic compounds and other dangerous substances. On site analyses revealed that the main part of the contamination in the upper 20 cm layer of the soil is essentially composed of combustion residues and charred compounds, with extremely high concentrations of hazardous metals: up to 26 398 mg/kg for Pb, 133 237 mg/kg for Zn and the astonishing content of 175 907 mg/kg for As [13]. Such values are clearly incompatible with any human activity and housing, farming and forestry are still forbidden in the Red Zone, after more than one century. Some towns and villages were never permitted to be rebuilt after the war either. Then, the extensive use, by both sides, of artillery shells loaded with chemical weapons too, during the combats, further contributed to the contamination of the land. Every year, several tons of unexploded shells are recovered, but it is estimated that it will take hundreds of years to completely clean the area at the current pace [14]. The restrictions within the forbidden area have evolved over time, with certain areas being reopened for limited activities. However, the cleanup efforts are ongoing and there are still significant challenges to overcome. In addition to the removal of unexploded ordnance, various ecological restoration

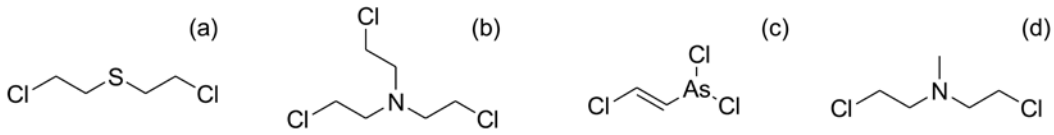
projects have been initiated to revive the biodiversity of the Red Zone. These projects aim to reintroduce native plant species, create habitats for wildlife and promote the overall ecological health of the area. The restoration of the Red Zone not only benefits the environment but also helps to preserve the memory and history of World War I.

4. The long-lasting burden of World War II offshore of Bari

On December 2nd, 1943, the harbour of Bari, in Southern Italy, underwent a severe bombing air raid: 12 vessels were damaged, 25 sunk and 3 ships were completely destroyed. One of the vessels was the *US Liberty Ship John Harvey*, with her hidden cargo of 2000 air bombs, each carrying about 30 kg of mustard agents, vesicant chemical warfare agents. The destruction of the vessel caused liquid sulfur mustard from the bombs to spill into waters already contaminated by oil from other damaged ships. The sailors who had abandoned their ships into the water got covered with the oily mixture, which resulted to be an ideal solvent for the sulfur mustard. Some mustard evaporated and mingled with the clouds of smoke and flame. The wounded were pulled from the water and sent to medical facilities whose personnel were unaware of the mustard gas. Medical staff focused on personnel with blast or fire injuries and little attention was given to those merely covered with oil. Many injuries caused by prolonged exposure to low concentrations of mustard might have been reduced by simple bathing or a change of clothes. Among, civilians, the first symptoms of mustard poisoning had appeared in 628 patients and medical staff, including blindness and chemical burns.

Bis(2-chloroethyl)sulfide and tris(2-chloroethyl)amine, commonly known as sulfur mustard and nitrogen mustard, respectively, and dichloro(2-chlorovinyl)arsine, also known as lewisite are the major highly toxic compounds threatening the aquatic environment close to Bari harbour (Scheme 2) [15]. Since the end of the war, injuries to fishermen and divers caused by partially corroded shells, leaking highly hazardous liquids found on the seabed are occasionally recorded on a regular basis [16]. Later, in 1999, the Italian Ministry of the Environment commissioned the Central Institute of Applied Marine Research to identify the sites affected by chemical weapons remnants, evaluate the bombshell integrity and assess potential the environmental impact on submarine species [10].

Scheme 2. Sulfur mustard (a), nitrogen mustard (b), lewisite (c) and Mustargen (d).



At the same time, it is worth highlighting that the U.S. internal final official report on the Bari mustard casualties raised attention onto the toxic effects on white blood cells generated by organosulfur alkylating molecules and paved the way to new strategies to the treatment of

cancer. Deeper studies indeed suggested the use of sulfur- and nitrogen-mustards to inhibit the fast-multiplying malignant white cells that invade and destroy healthy tissue. The pioneer studies showed how these harmful substances, in carefully calibrated doses and under controlled conditions, could be used to heal, as targeted medicines against cancer. So, in 1949, Mustargen (mechlorethamine; Scheme 2) became the first experimental active molecule approved to treat non-Hodgkin's lymphoma, thus initiating the age of chemotherapy in oncology [17]. The very high toxicity of such nitrogen-mustard molecule is due to its extremely high tendency to react and interfere with any biochemical macromolecule, including DNA, RNA and proteins. Mustargen is therefore an exemplar case of dual-use chemical, with either a pacific application, as a medicine, or an illicit one, as a vesicant chemical warfare agent.

5. Land mines

Some seventy-eight countries are affected by land mines, which kill or maim 15000 to 20000 people every year. Approximately 80% of casualties are civilians, with children the most affected age group. An estimated average of 50% of deaths occurs within hours after the blast. In recent years, mines have been used increasingly as weapons of terror against local civilian populations. Nevertheless, along with the obvious danger of explosion, buried and forgotten land mines can cause environmental contamination. In these cases too, munition-related chemicals, such as explosives and perchlorate compounds, can leach out from the obsolete device and enter soil and groundwater. In Table 1, the countries most heavily affected by landmines are listed, with a rough estimation of the number of pieces still present within their territories.

Country	**Millions of mines (estimation)**
Egypt	23
Iran	16
Afghanistan	10
Angola	10
Iraq	10
China	10
Cambodia	7
Kuwait	5
Vietnam	3.5

Tab 1. List of countries most heavily affected by landmines, ref. [18].

Egypt is the most heavily mined country in the world (by number). However, landmines pose a persistent threat to local people all over the African continent, including Ethiopia, Somalia, Nigeria, Senegal, Angola, Kenya, Uganda and South Africa, just to mention a few. In the tropical regions, typhoons and floods often displace and spread landmines, further aggravating the problem. In Mozambique, for instance, as much as 70% of the country is now contaminated with mines because of floods [19].

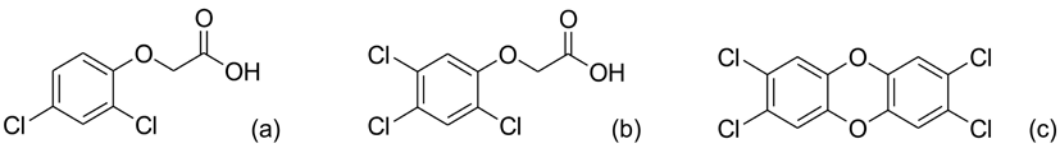
6. The heavy legacy of Vietnam War

In terms of dropped bomb per capita, Laos is considered the most heavily bombed country in the world [20]. During the Vietnam War, more than 2 million tons of ordnance were dropped on Laos in some 500 000 bombing missions carried out by the U.S. armed forces. In most cases, anti-personnel cluster bombs were employed, each of which contained hundreds of individual smaller bomblets (called "bombies"), about the size of an orange. One third of these munitions did not detonate, according to most estimations [21]. In addition, more than half of the Laotian land has been declared "severely contaminated" with artillery and mortar shells, mines, grenades, rockets and other explosive devices from various origins. The ubiquitous presence of unexploded ordnance is a never-ending obstacle to agriculture and a special threat to children, who are attracted by such toy-like devices.

About 288 million cluster munitions and about 75 million unexploded bombs were left across Laos after the end of the war [22]. Likewise, in the neighbouring Vietnam, some 800 000 tons of landmines and unexploded ordnance are estimated to be still buried in the forests and in mountains. Although from 1996 to 2009 more than 1 million of unexploded devices were destroyed, between 1999 and 2008 more than 2100 casualties (including 834 deaths) were recorded from incidents. From 1975 to 2015, up to 100 000 people have been injured or killed by bombs left over by the second Indochina war [22].

However, the heaviest damages to environment recorded during the military campaigns in Vietnam are ascribed to the massive use of defoliation agents as an unconventional weapon. Agent Orange is the name of a mixture of herbicides used by U.S. military forces in the period 1962-1971 during the Vietnam War. It was used for the two-fold purpose of defoliating forest areas that might hide Viet Cong and North Vietnamese forces and destroying crops that might feed the enemy. The defoliant formulation, sprayed from low-flying airplanes, contained approximately equal amounts of the unpurified butyl esters of 2,4-dichlorophenoxyacetic acid (2,4-D) and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) (Scheme 3). Because of its impurities, Agent Orange contained small, variable proportions of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (commonly called "dioxin"), that was present as a by-product of the manufacture of 2,4,5-T. Dioxin is a widely-known highly toxic contaminant, even in microgram quantities [23]. The total volume of sprayed herbicides was about 75800 tons of Agent Orange, contaminated by ca. 170 kg of pure dioxin, that were therefore dropped on Vietnam [24]. Agent Orange was later proven to cause serious health issues, including cancer, birth defects, dermal rashes and severe psychological and neurological problems among the Vietnamese people, as well as among returning U.S. veterans and their families.

Scheme 3. The active ingredients 2,4-D (a) and 2,4,5-T (b) and the "impurity" 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (c).



7. The use of depleted uranium in the Balkan area

Depleted uranium (^{238}U) is a highly dense, slightly radioactive, metal co-generated in the process through which natural uranium is enriched to produce reactor fuel and nuclear weapons components. Depleted uranium has been used for civil and military purposes for many years. Both civil and military uses of ^{238}U are based on its density (ca. 1.7 times as dense as lead) and metallurgical properties. Likewise, potential health threats are related to the chemical and radioactive properties of it. This metal is used in radiation shielding, military munitions and armour, counterweights and ballast for some missiles, yachts and aircraft. Military uranium-based munitions, first used in combat in the first Gulf War, take advantage of ^{238}U hardness and pyrophoric nature on impact. In fact, depleted uranium penetrators indeed become sharper as they penetrate armoured barriers and are therefore able to pierce more effectively thicker armour than conventional shells [25].

Depleted uranium weapons were used in the Balkans conflict, raising concerns about possible long-term health and environmental effects [26]. A monitoring program was hence implemented to examine the environmental impacts of ^{238}U contamination in soil, drinking water, air and vegetation samples [26]. Additionally, a medical surveillance program was established to identify any potential health effects on professional personnel who were exposed to depleted uranium during the conflict.

There has been much study and controversy about detrimental effects upon exposure to depleted uranium weapons, especially in the battlefields where such munitions were used in the 1990-1991 Gulf War and in the 1999 NATO bombing of Yugoslavia. About 320 tons of depleted uranium were used in ammunitions during the first Gulf War in 1991 and an estimation of 3 tons were discharged on Bosnia and Herzegovina between 1994 and 1995, 1 ton in Serbia and Montenegro and ca. 11 tons in Kosovo in 1999 [27]. Ingesting or inhaling quantities of depleted uranium is dangerous, as it depresses renal function and enhances the risk of developing various types of cancers.

With regards to specific risk assessment studies carried out in the Balkan region, no direct links between depleted uranium exposure and negative health effects have been evidenced [26]. However, ingestion and inhalation of fine dust particles produced by burning depleted uranium anti-tank ammunition can lead to significant toxicological and radio-toxicological risks of late effects on human health [28].

Aiming at mitigating such issues, the International Coalition to Ban Uranium Weapons was created in 2003 in Belgium, collecting more than 160 groups in 33 countries, to encourage the ban on the use, transport, manufacture, sale and export of all depleted uranium weapons [29]. The Coalition also promotes health monitoring and compensation for communities affected by the use of ^{238}U weapons and the environmental remediation of such sites. The main source of concern indeed is the ultrafine dust produced by such weapons when they hit the target, generating extremely high temperatures (up to 3000 °C) at the impact point and causing a sudden vaporization of all materials involved in the explosion. Such ultrafine particulate dust, typically composed by agglomerates of micrometre-sized inorganic oxides, among which uranium oxides are present too, can be breathed and enter human body through the airways and

can contaminate groundwater and soil in the proximity of the combat areas [30]. In detail, the cleanup of depleted uranium in Kosovo was not completed, with some areas receiving more assistance from the local government for decontamination than others [31]. A United Nations Environment Programme report on the impact of depleted uranium on Serbia and Montenegro found no significant, widespread contamination [32]. Some local Serbian politicians, however, have disputed these statements and highlighted an increased incidence in the number deaths from malignant tumours in the country [33, 34].

8. Modern warfare in Eastern Europe

When combats are carried out in densely industrialised zones and/or in areas of relevant environmental interest (*e.g.*, natural parks, special biotopes, specific ecosystems) the impact on the environment of warfare can be amplified and, sometimes, irreversible. Industrial facilities can be damaged by explosive weapons, leading to unintentional chemical spills and water and land contamination [35]. Such leaks are often considered as "collateral damages" and thus detrimental effects inflicted as incidental action to a necessary military action. In 1999, during the air strikes against Yugoslavia, NATO airforces bombed fertilizer and polyvinylchloride manufacturing plants and an oil refinery in Pancevo, near Belgrade. The blast caused the release of toxic fumes in the atmosphere and thousands of tons of hazardous chemicals containing mercury, dioxins, vinylchloride and their byproducts into air and in the nearby Danube river [36].

A larger-scale and still ongoing environmental disaster is occurring in the territories of Eastern Ukraine, due to the war operations in that area since February 2022. The combats are the most prominent conflict in Europe since the World War II and give rise to very heavy, multifaceted geopolitical, economic and social implications on population and the ecosystem. Water shortages and deteriorating sanitary conditions have been evident since the beginning, as water supply network and healthcare infrastructure have been hit. Air quality in densely populated areas is adversely affected due to constant bombarding. Fires in large fuel deposits generate relevant amounts of micrometric particulate matter that contaminate air in urban areas, affecting the respiratory system of fragile exposed population, in particular children and elderly people. Likewise, a large fraction of buildings in Ukraine contains asbestos components, the country being among the most important producers and manufacturers of this fire-resistant mineral in the world until 2005 (Ukraine used 183 000 tons, solely for the internal manufacturing in 2005). Only in 2012, during the "International Asbestos Conference" held in Kyiv (21-22 Nov), started the project for phasing out asbestos production and use, followed by the total ban in 2017 [37, 38]. The extensive destruction of civil and military structures in towns and villages thus enhances the risk of non-negligible amounts of hazardous asbestos-containing dusts in debris fall-out in urban areas.

A further remarkable threat is connected to the contamination of underground water sources due to percolation of highly contaminated wastewaters from mining industry, especially in the Donbass region. Sudden interruptions in excavation activities and failures in the pumping and management of liquid waste effluents from mines, containing very high concentrations of corrosive metal salts and toxic eluates, often lead to uncontrolled and hidden permeation of pol-

lutants into the deep layers of underground waterbodies, thus contaminating the local sources of fresh water for the following decades.

Risks of leakage of radioactive materials or waste from nuclear plants and spent fissile fuel stocking sites is present too. It is worth recalling, in fact, that 15 nuclear power reactors are active in Ukraine, the largest plant being in Zhaporizhzhya, and as far as in 2020 half of the national energy need was obtained from nuclear fission [39]. The physical, chemical and biological characteristics of soil have been impacted due to shelling and explosions, as a result of which, agriculture has been severely affected. Military actions have caused large-scale deforestation and uncontrolled wildfires. There are also concerns for biodiversity loss and species extinction in the long term [40]. More than 40% of valuable natural areas of Ukraine, including national parks and unique biotopes, have been heavily or irreversibly affected by military operations. In this perspective, the Ministry of Ecology and Natural Resources of Ukraine in late 2022 has reported, so far, some 330 cases of crime against the ecosystems and more than 2400 cases with severe consequences on the environment of military actions [41].

The United Nations Environment Programme, upon request by the Government of Ukraine, published a preliminary report to evaluate the character, magnitude and relevancy of conflict-related environmental impact and to figure out potential remediation requirements [42]. The report presents a snapshot, although not comprehensive, of the damage inflicted on country's ecosystem as well as on public health, suggesting priorities for future on-field assessment and verification work. Initial information displays how Ukraine, that is a highly industrialised country, previously burdened by a long-lasting legacy of environmental challenges left by the Soviet Union age, is now facing a complex and ever-growing environmental crisis, exacerbated by the dramatic war situation. It is therefore highly probable that the country and the region will suffer from a heavy toxic legacy long after the end of the conflict.

9. Conclusions

As we primarily remember sacrifices and sufferance of all populations worldwide in wartime, it is equally important to protect and preserve the global environment, allowing future generations to live in a world free from war and its devastating consequences on health and ecosystems.

War has a devastating impact on the environment that inevitably affects humanity. Armed conflicts can cause the destruction of infrastructure (roads, bridges, buildings and other critical infrastructure) making it difficult to access food, water, and health services. Moreover, it causes air and water pollution from the use of weapons, ammunition, and other hazardous material leading to respiratory, gastrointestinal, and other illnesses. War also causes loss of biodiversity through habitat destruction, pollution and poaching, with long-term impacts. Thus, war affects not only the people who inhabit the earth today, but also future generations.

The long-lasting impact of armed conflicts and residual weapons on human health and nature is a theme deserving further investigation and attention. The presence of unexploded ordnance and contamination of soil and waterbodies caused by past military activity highlight the need for responsible environmental stewardship, to prevent further environmental damages in times of local conflicts too. Likewise, the impressively challenging and expensive efforts for

the decontamination and remediation of huge areas of war scenarios of the 20th century (the WWI Red Zone in Northern France, the battlefields in Vietnam or the former-Yugoslavia region in the Balkans) must serve as a reminder of the hardly reversible footprint of conflicts on the environment.

Modern warfare, in addition, hampers and jeopardises the efforts to cope with key sustainable development goals, such as climate change mitigation, conservation and protection of biodiversity and pollution control. Along with these aspects, the negative aftermaths of war on essential services such as healthcare, social security, education and welfare amenities are experienced for a long time by populations.

To mitigate such kind of damages to ecosystems and make the perpetrators accountable in the future, new and stricter international rules are needed to safeguard the environment during armed conflicts and to consider environmental crimes as relevant as crimes against humankind. Damages to the environment in wartimes, indeed, should not be considered as unavoidable "collateral damages" anymore, since environmental and human wellbeing are intimately linked.

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