frontiers | Frontiers in Environmental Science

TYPE Review
PUBLISHED 06 February 2025
DOI 10.3389/fenvs.2025.1539520

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OPEN ACCESS

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RECEIVED 05 December 2024
ACCEPTED 17 January 2025
PUBLISHED 06 February 2025

CITATION
Wirtu YD and Abdela U (2025) Impact of war on the environment: ecocide.
Front. Environ. Sci. 13:1539520.
doi: 10.3389/fenvs.2025.1539520

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Impact of war on the environment: ecocide

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This paper reviews the militaristic consequences on Mother Earth and in particular ecocide or the mass degradation of the biological forms in regards to war. Wars are recorded from the ancient Egyptian dynasty to the modern era, and all are left concerning effects on mother nature such as deforestation, loss of biodiversity, soil erosion, and water, and air pollution. Some conflicts that are especially noted are the Vietnam War, Gulf War, and contemporary wars in Ukraine which are considered as examples of ecocide in today's context. To provide a clearer understanding of our methodology, we employed a comprehensive literature review approach. This involved systematically analyzing existing studies that document the environmental impacts of warfare across various historical and contemporary conflicts. We categorized the findings based on specific environmental consequences, such as deforestation, biodiversity loss, and pollution. Additionally, we incorporated case studies from significant wars to illustrate patterns of ecocide. The paper looks at how environmental hazard is performed through wars such as direct environmental destructive activities like bombings migration of populations and their needs and socio-economic pursuits. Legal instruments especially those at the international level and international environmental law concerning ecocide as a developing crime are also examined for the problem of ecological injustice. Finally, the review looks at rehabilitation and reconstruction measures including community-based efforts like reforestation and the restoration of ecosystems. The paper finally ends by advocating the threats of international ecocide by calling for international cooperation and treaties on ecocide and no environmental degradation in post-war countries.

KEYWORDS

ecocide, war environmental impact, biodiversity loss, military conflict, international environmental law, environmental justice

1 Introduction

Traditionally, war could only be seen regarding the affected population and their socio-political and economic system. However, the effects of warfare on the surroundings should also be examined as they are equally if not more destructive.

Ecocide refers to unlawful or wanton acts committed with the knowledge that there is a substantial likelihood of severe and either widespread or long-term damage to the environment caused by those acts. Initially coined during the Vietnam War to describe the environmental destruction caused by herbicides like Agent Orange, ecocide has been proposed as an international crime akin to genocide or war crimes. This definition, developed by the Independent Expert Panel for the Legal Definition of Ecocide, emphasizes accountability for actions that result in significant environmental harm, distinguishing them from lawful economic activities that may also cause damage but do

not meet this threshold of reckless (Trigt, 2021; Minkova, 2023). To ensure consistency, this definition will be applied uniformly across case studies.

Furthermore, numerous definitions of ecocide can enrich the analysis. For instance, Weisberg's work highlights ecocide as a concept emerging from military conflicts, particularly concerning the environmental devastation caused during the Vietnam War through the use of chemical agents like Agent Orange (Barry Weisberg, 1972). Additionally, Higgins has defined ecocide as the extensive destruction or loss of ecosystems, underscoring its relevance beyond wartime contexts (Barry Weisberg, 1972; Higgins et al., 2013). The Independent Expert Panel also notes that ecocide includes descriptions of mass damage or ecosystem destruction committed with knowledge of the risks (Panigaj and Berníková, 2023). By incorporating these varied definitions, a broader perspective on ecocide and its implications can be achieved (World Economic Forum, 2021; Arifin et al., 2024).

Ecocide is rapidly gaining recognition as a crucial issue in global environmental and development debates, particularly regarding its potential role as an international legal term. Defined as unlawful or wanton acts causing significant harm to the environment, ecocide aims to hold individuals and corporations accountable for environmental destruction. Efforts to incorporate ecocide into international law, such as proposals to amend the Rome Statute, reflect a growing consensus on the need for legal mechanisms to protect ecosystems. While challenges remain such as establishing clear definitions and ensuring international consensus the recognition of ecocide could fundamentally transform how environmental harm is addressed legally, promoting accountability and sustainability on a global scale (Higgins et al., 2013; Panigaj and Berníková, 2023).

Throughout history, wars have not only destroyed society but also had profound negative effects on the environment. This is especially true in modern warfare where the scale of degradation caused is unprecedented. A case in point is the Vietnam War where there was still some land left, Commander of the Vietnam Military Region 3 Nguyen Van Hoang ordered US troops to spray chemical defoliants like Agent Orange across the country to clear out weapons making the land forever barren and toxic (Terms, 2016). Not unlike, during the Gulf War, immense quantities of pollutants were added to the air by igniting Kuwaiti oil fields which also tarnished the climate and environment (Gerges, 1993; Mach et al., 2019; Racioppi et al., 2022). Regardless of these stark illustrations of high instances of ecocide, international law is still lacking in its capacity to deal with the problem of environmental crimes in conflicts. While the Geneva Conventions focus on atrocities committed against persons, ecology is only assured by a few countries although it fails to address all the relevant points thus making it inadequate (Higgins et al., 2013).

The environmental impact of war is immense, affecting not only the immediate landscapes but also long-term ecological stability. Direct effects include the destruction of forests, contamination of water sources, and the degradation of arable land (Gleditsch, 2015). Indirect consequences, such as biodiversity loss and the disruption of ecosystems due to population displacement and resource exploitation, are equally severe. Yet, the environmental consequences of warfare are often overshadowed by the more immediate human costs, leaving the ecological devastation under-addressed in post-conflict recovery efforts and legal frameworks (Homer-Dixon, 1999; Abrahams, 2018).

Current research primarily focuses on the human and economic impacts of war, with less attention paid to the environmental costs. While individual case studies highlight specific instances of environmental damage, there is a lack of comprehensive studies examining the broader patterns of environmental degradation caused by warfare (Pencheon, 2001; Leal Filho et al., 2024). Moreover, the concept of ecocide as a distinct legal and moral issue remains underdeveloped, with few studies exploring how it could be prosecuted under international law (Higgins et al., 2013; Panigaj and Berníková, 2023). This research gap underscores the need for a more thorough exploration of how war contributes to ecocide and how legal frameworks can be strengthened to protect the environment during and after conflicts.

This review aims to explore the environmental impacts of war, with a specific focus on ecocide. By analyzing case studies from historical and modern conflicts, it seeks to understand the mechanisms through which military actions lead to large-scale environmental destruction. The review also examines the challenges of prosecuting ecocide under existing legal frameworks and contributes to the growing discourse on recognizing ecocide as an international crime. The objective is to highlight the urgent need for stronger legal protections for the environment in conflict zones and to promote greater accountability for environmental destruction during warfare.

This review is significant because it addresses the often neglected issue of environmental destruction in war. By focusing on ecocide, it aims to raise awareness of the long-term ecological impacts of conflicts and the importance of integrating environmental protection into international laws governing armed conflict. The study also contributes to the global discussion on the potential recognition of ecocide as an international crime, offering insights into how legal frameworks can be strengthened to hold perpetrators accountable for environmental damage (Aini and Banjarani, 2018; Panigaj and Berníková, 2023). Additionally, the review emphasizes the importance of post-war environmental rehabilitation, which is crucial for restoring ecosystems and ensuring sustainable development in regions affected by conflict (Salih, 2020). Understanding the environmental consequences of war is essential for creating a more sustainable future, where ecosystems are protected, and the long-term health of the planet is prioritized.

2 Approach

This review has selected 188 studies published between 2000 and 2024. An adequate literature analysis has been conducted to examine the most recent data on the war and its Environmental impact: Ecocide. For a comprehensive review of the environmental impact of war with a focus on ecocide, a range of multidisciplinary databases was invaluable. Scopus and Web of Science are ideal for accessing a broad range of high-impact environmental science, policy, and legal studies related to ecocide and international relations. PubMed offers extensive resources on the health impacts of war on the environment, toxicology, and ecosystem studies, making it useful for understanding the toxic effects of warfare on biodiversity and human health. JSTOR provides rich historical and humanities-based

perspectives, offering insight into how wars have affected environments through different eras. Google Scholar serves as a comprehensive source for diverse academic literature, including both journal articles and scholarly books, and is particularly helpful for identifying a wide range of perspectives on ecocide. Lastly, ScienceDirect provides strong scientific coverage, particularly for environmental science and toxicology, which can be critical for exploring specific case studies and empirical research on the Environmental degradation associated with war. Together, these databases form a robust foundation for examining the multi-faceted impact of warfare on ecosystems and understanding ecocide in a contemporary context.

To search effectively for studies on the environmental impact of war, especially focusing on ecocide, a combination of search strings can be applied across multiple databases. Terms like "ecocide" "environmental impact of war" "war-related environmental degradation" or "ecological destruction by military conflict" capture resources that specifically address the broad ecological damage resulting from warfare. Additional phrases such as "impact of warfare on ecosystems" "biodiversity loss" "chemical warfare" and "environmental contamination" target studies exploring the direct damage to biodiversity and contamination caused by war chemicals and weapons. To find information on post-conflict scenarios, search strings like "post-war environmental recovery" "ecological restoration after conflict" and "long-term effects of war on biodiversity" can yield insights into the lasting consequences and efforts at ecological restoration. Keywords including "international law on ecocide" or "ecocide as a war crime" also help identify literature on potential legal protections against environmental destruction in conflict zones, while "natural resource exploitation in war zones" and "environmental consequences" and "military-induced habitat destruction" can uncover articles focusing on war-induced habitat destruction and resource exploitation. Together, these search strings provide a comprehensive approach to capturing various aspects of ecocide, from direct environmental damage to legal and restorative perspectives.

For this review on the environmental impacts of war, specifically ecocide, inclusion criteria were focused on studies that provide recent, peer-reviewed, and relevant content. Studies published within the last 20 years were prioritized to ensure up-to-date insights, although seminal older works with a significant impact on the field may also be included. Only English-language publications were considered to maintain consistency and accessibility. Relevant studies include peer-reviewed journal articles, authoritative books, and reputable reports that explore war-related environmental impacts, cases of ecocide, or legal perspectives on environmental protection during the conflict. Additionally, studies that focus directly on ecological degradation due to war, as well as potential frameworks for prosecuting ecocide, were included.

Conversely, exclusion criteria were removed from studies published before 2000 unless foundational to the concept of ecocide or the environmental impacts of warfare. Non-peer-reviewed sources, editorial pieces, and opinion articles were excluded to ensure the review is based on rigorously vetted information. Studies that only cover the human or economic costs of war without discussing environmental implications were also excluded, as they fall outside the primary scope of ecocide and ecosystem degradation. Non-English publications and any materials unrelated to the intersection of war and environmental damage were omitted to maintain relevance and specificity.

3 Result and discussion

3.1 Military technologies and their environmental footprint

Military technologies, particularly advanced weaponry and drones, contribute significantly to environmental degradation during conflicts. The ecological impact of these technologies is profound, primarily due to the contamination associated with their use and the infrastructure required to support them. For instance, the deployment of drones and other advanced systems often involves extensive military bases that lead to habitat destruction and soil degradation through excavation and vegetation removal, increasing the risk of invasive species (Qumsiyeh, 2024).

Additionally, the use of munitions results in direct contamination from heavy metals and hazardous chemicals, which can persist in the environment long after conflicts have ended (Lawrence et al., 2015; Akhundov, 2024a). This contamination not only affects local ecosystems but also poses risks to human health in surrounding civilian areas (Akhundov, 2024b). As military operations increasingly rely on these technologies, understanding their long-term ecological consequences is crucial for mitigating future environmental harm (Teeratanabodee, 2022).

3.1.1 Drones and their environmental impact

Drones, or Unmanned Aerial Vehicles (UAVs), are often celebrated for their efficiency and potential to reduce carbon footprints across various applications, including military operations. However, their operational impacts during conflicts frequently offset their environmental advantages. While drones can be more energy-efficient than traditional aircraft, they still consume a significant amount of energy, especially when powered by non-renewable sources. Consequently, the environmental footprint of drone operations varies considerably based on the energy mix utilized for charging and operation (Park et al., 2018; Quamar et al., 2023). Additionally, the deployment of drones in military contexts can disrupt ecosystems and lead to habitat destruction. Aerial assaults, for example, have been associated with substantial alterations to habitats and pollution, which contribute to biodiversity loss. This issue is particularly pronounced in areas where drones are employed for surveillance or combat, as their activities can disturb sensitive ecosystems and negatively affect local wildlife populations (Lawrence et al., 2015).

Emerging trends indicate that current wars should be addressed specifically due to new environmental knowledge that was not available during the Vietnam War, particularly regarding the ecological impacts of drone warfare. The increasing reliance on drones in modern military operations has introduced unique environmental challenges. For instance, while drones may reduce carbon emissions compared to traditional aircraft in some contexts,

their use in explosive attacks can generate significant pollutants that pose risks to human health and ecosystems (CEOBS, 2023). Furthermore, as drone technology evolves with advancements in artificial intelligence and autonomous systems, there is a growing concern about the potential for increased environmental degradation due to less oversight in targeting decisions. This shift raises critical questions about the long-term ecological consequences of deploying drones in diverse conflict scenarios. Understanding these emerging trends is crucial for developing comprehensive strategies that mitigate the environmental impacts of drone warfare while balancing military effectiveness with ecological preservation.

3.1.2 Advanced weaponry and ecological consequences

Modern weaponry, including precision-guided munitions and heavy artillery systems, presents distinct challenges to environmental health. One significant issue is pollution resulting from munitions; the detonation of explosives releases harmful pollutants into the air and soil. Heavy metals from munitions can contaminate local ecosystems, adversely affecting soil health and water quality. For instance, lead from bullets can persist in the environment, leading to decreased vegetation growth and reduced species richness over time (Lawrence et al., 2015). Additionally, military operations often involve the use of chemicals that can have enduring impacts on the environment. Fuels and lubricants utilized in military vehicles are prone to leaking into the soil and waterways, resulting in toxic contamination that jeopardizes both terrestrial and aquatic life (Lawrence et al., 2015).

The complexities surrounding military operations often lead to insufficient accountability for environmental damage caused by advanced weaponry. Political interests may hinder efforts to implement stricter regulations or to hold parties accountable for ecological harm resulting from warfare (Cottrell et al., 2022).

Political resistance can manifest in various ways. Governments may prioritize national security over environmental protection, viewing military operations as essential for maintaining power or territorial integrity (UN Environment Programme, 2021). This perspective can lead to a reluctance to acknowledge or address the environmental consequences of military actions, especially when those actions are justified under the guise of national defense or counterterrorism. Additionally, powerful defense lobbies may exert influence on policymakers to resist regulations that could limit military operations or impose additional costs related to environmental remediation.

Moreover, international cooperation on environmental issues related to warfare is often hampered by geopolitical tensions. Countries involved in conflicts may be unwilling to engage in discussions about environmental accountability if they perceive such discussions as threats to their sovereignty or military capabilities (Westing, 2003). This lack of cooperation can prevent the establishment of comprehensive international legal frameworks that address ecocide effectively.

The enforcement mechanisms necessary for prosecuting ecocide are also often weak or non-existent in conflict situations (CEOBS, 2017). Even when legal frameworks exist, they may lack the political backing required for effective implementation. For example, international courts may face challenges in gathering evidence or securing jurisdiction over military actions that result in environmental harm. Additionally, local communities affected by environmental degradation often lack access to legal recourse due to inadequate legal representation or fear of retaliation.

Without addressing these political challenges, efforts to mitigate the ecological consequences of modern warfare will remain ineffective. It is crucial for policymakers and international organizations to recognize the interconnectedness of environmental protection and conflict resolution. Establishing robust legal frameworks that prioritize ecological considerations alongside military objectives requires a concerted effort to overcome political resistance at both national and international levels.

3.2 Environmental impacts of war

3.2.1 War on biodiversity

The environmental impacts of warfare are far-reaching, with biodiversity loss being one of the most severe consequences. This biodiversity loss includes species extinction, habitat destruction, pollution, and the introduction of invasive species, all of which create complex disruptions in ecosystems. Biodiversity is fundamental to ecosystem resilience and supports numerous ecological processes that benefit both humans and wildlife. The loss of biodiversity caused by warfare therefore has enduring and widespread implications for environmental stability and human wellbeing (Machlis and Hanson, 2011).

It is essential to explore not only the direct impacts of warfare on biodiversity but also the indirect effects that can arise from socio-economic changes, such as increased poaching and illegal resource extraction during times of conflict (CEOBS, 2022). Additionally, understanding how geopolitical dynamics influence conservation efforts in conflict zones can provide a more nuanced perspective on the challenges faced by biodiversity in these areas.

Moreover, while some studies highlight the immediate detrimental effects of war on biodiversity, they often overlook long-term consequences such as shifts in land use patterns post-conflict that can lead to further habitat degradation (UNEP, 2007). Addressing these gaps will enhance our understanding of how armed conflict exacerbates existing threats to biodiversity and complicates conservation efforts.

3.2.1.1 Species extinction

Warfare accelerates species extinction by directly disrupting ecosystems and destroying habitats, leading to rapid declines in populations and, in some cases, the disappearance of species. Many conflict zones are biodiversity hotspots, rich in unique species and habitats, but also subject to intense environmental stress due to human activity. War increases this stress through activities such as deforestation, pollution, and the inadvertent introduction of invasive species, which can disrupt ecosystems and create conditions that lead to species extinctions.

During the Vietnam War, for instance, the widespread use of herbicides like Agent Orange resulted in the defoliation of vast forested areas, causing extensive ecological damage and affecting many species, including the endangered Asian elephant and Indochinese tiger (Kroening et al., 2011) These species, which require dense forest habitats, were pushed to the brink as their

living environments were destroyed or poisoned. The destruction of keystone species has further ripple effects throughout ecosystems, as these species often play critical roles in maintaining ecological balance. When keystone species are lost, it can destabilize entire communities, leading to further extinctions and significant biodiversity declines (Christian, 2023).

According to Olson and Morton (2019), the use of herbicides like Agent Orange destroyed over 3 million acres of forested land, which not only disrupted local biodiversity but also contributed to soil erosion and loss of habitat for numerous species. This loss has long-term implications for carbon storage and climate regulation in the region (Olson and Morton, 2019).

War-induced hunting and poaching of wildlife also intensify the risk of extinction, especially for large mammals. During civil conflicts in Africa, for example, poaching surged as combatants and civilians alike turned to wildlife for sustenance and financial gain. This led to alarming reductions in populations of threatened species, including elephants and gorillas (Rist et al., 2023). Such declines are not merely losses of individual species but can signal the beginning of a collapse in broader ecological networks, as the absence of these species disrupts predator-prey relationships and affects vegetation through changes in herbivory.

3.2.1.2 Habitat destruction

Habitat destruction is one of the most direct and visible impacts of war on biodiversity. Military operations frequently require clearing land to establish bases, training areas, and logistics routes. In the process, vast areas of natural habitats are often damaged or destroyed. Forests, wetlands, and other sensitive ecosystems are cleared or degraded, reducing viable living space for wildlife and disrupting ecological processes. Habitat destruction of this magnitude is frequently irreversible, especially in ecologically fragile regions.

The Persian Gulf War exemplifies the catastrophic environmental consequences of such destruction, with intentional oil spills and the burning of oil wells causing severe damage to coastal and marine ecosystems in Kuwait and nearby areas. The destruction of these habitats had long-lasting effects on marine and coastal species, as the oil contamination persisted in sediments and continued to affect water quality and food sources for years afterward (Linden et al., 2004). The loss and fragmentation of habitats like these pose significant risks to biodiversity, as species that rely on intact ecosystems are often unable to adapt to degraded conditions, leading to local extinctions.

Tropical regions, particularly rainforests, are especially vulnerable to deforestation caused by conflict. In Colombia, for instance, protracted conflict has resulted in extensive deforestation in biodiverse areas, particularly within the Amazon rainforest. This habitat loss has jeopardized countless species, many of which are endemic and already endangered (van Solinge, 2018; Bautista-Cespedes et al., 2021). The destruction of tropical forests not only threatens biodiversity but also affects global environmental stability by contributing to soil erosion, disrupting water cycles, and increasing vulnerability to climate change. These areas are vital carbon sinks, and their destruction exacerbates climate change impacts, affecting ecosystems globally.

3.2.1.3 Pollution and contamination

Pollution from military activities is a significant driver of biodiversity loss, particularly through soil, water, and air contamination. The use of chemical weapons, explosives, and heavy machinery releases a range of pollutants that accumulate in the environment and impact species' health. These contaminants include heavy metals, oil, and other chemical toxins, which accumulate in the tissues of organisms and move up the food chain, a process known as bioaccumulation. This pollution reduces reproductive success, increases mortality rates, and causes developmental issues in wildlife, further contributing to biodiversity decline (Sheoran, 2010).

Water pollution resulting from military activities can also devastate aquatic ecosystems. In Iraq, for instance, the marshlands that once thrived in Mesopotamia were devastated by pollution during and after the Gulf War. Oil spills, chemical pollutants, and salinization disrupted the region's hydrology and destroyed habitats for fish, birds, and other species dependent on these water systems (Nations and Programme, 2001). The impacts of such pollution are often long-term, as contaminants can persist in water and sediments for decades, affecting generations of species and complicating restoration efforts.

Unexploded ordnance and landmines represent additional pollution threats, as they render large areas uninhabitable for both wildlife and humans, preventing ecological recovery. These remnants of war continue to pose risks long after conflicts end. In the Balkans, landmines from past conflicts still pose significant threats to biodiversity and ecosystem functionality, obstructing both wildlife movement and habitat recovery (Nachón, 2004). This type of contamination creates "no-go zones" where neither humans nor animals can safely exist, effectively fragmenting habitats and further threatening species' survival.

A report by Abbarra et al. (2021) indicated that in Syria, military operations have led to a 30% reduction in water quality due to contamination from munitions and chemical spills, exacerbating existing water scarcity issues. The study highlighted that regions with ongoing conflict experienced higher levels of pollutants such as heavy metals and nitrates, which pose serious health risks to local communities (Abbaraa et al., 2021).

3.2.1.4 Introduction of invasive species

The movement of troops, equipment, and supplies across regions during warfare frequently leads to the introduction of non-native species into new environments. These invasive species, which lack natural predators in their new settings, can outcompete native flora and fauna, leading to biodiversity loss. The ecological effects of invasive species introduced during military conflicts are profound, as they often alter habitat structure, resource availability, and species interactions in ways that disrupt native ecosystems.

The Iraq War, for instance, saw the introduction of non-native plants and animals that subsequently spread across local ecosystems. These invasive species altered habitat conditions, making it more challenging for native species to thrive. In many cases, invasive species can alter soil composition, water availability, or even the physical structure of ecosystems, causing further stress to native populations (Santini et al., 2023). Once established, invasive species

can be difficult to control and may permanently alter ecosystems, displacing native species and reducing biodiversity.

3.2.1.5 Indirect effects on biodiversity

War's indirect impacts on biodiversity are also significant. Environmental regulations and conservation programs are often weakened or disregarded in times of conflict as resources are diverted to support military efforts. This deprioritization of environmental protection allows for increased illegal logging, mining, and hunting, which further threaten biodiversity. In regions affected by prolonged conflict, such as the Democratic Republic of Congo, weak environmental enforcement has led to extensive habitat destruction, undermining conservation efforts and putting additional pressure on endangered species (McNeely, 2003).

Human displacement caused by conflict also affects biodiversity, as displaced populations often rely on nearby ecosystems for survival, leading to overharvesting of resources and further degradation. In addition to direct overuse, displacement can lead to unsustainable agricultural practices in ecologically sensitive areas, resulting in soil erosion and loss of native vegetation. This degradation diminishes ecosystem resilience, making it harder for biodiversity to recover once conflicts end.

Generally, the environmental impacts of war on biodiversity are extensive and complex, leading to species extinction, habitat destruction, pollution, and the spread of invasive species. These effects disrupt entire ecosystems and diminish biodiversity, ultimately threatening the stability and functionality of the environment. The cumulative impacts of biodiversity loss from warfare not only harm natural systems but also pose long-term risks to human societies, underscoring the need for integrating environmental protections in conflict zones and considering ecocide as an actionable offense under international law.

3.2.2 Impacts of war on water quality

Water pollution is one of war's most immediate and lasting environmental impacts, with severe consequences for aquatic ecosystems, human health, and biodiversity. Military operations often involve extensive use of hazardous substances, chemicals, and heavy metals that contaminate water bodies, affecting entire ecosystems and communities that depend on these resources. This section delves into the mechanisms by which warfare contributes to water pollution, its impacts on aquatic ecosystems, and its broader implications for the environment and human populations.

3.2.2.1 Sources of water pollution during warfare

3.2.2.1.1 Chemical weapons and explosive. Chemical weapons, including nerve agents, mustard gas, and toxic organophosphates, are dangerous substances deployed in warfare to harm or kill, but they also cause severe environmental contamination. When these substances enter water systems, they pose long-lasting risks to ecosystems and human health due to their toxicity and persistence in natural environments if they are not neutralized (EPA, 2011).

The impact of chemical weapons on water bodies is significant during and after warfare, as contaminants from these weapons leach into aquatic ecosystems, threatening biodiversity and public safety (Corredor et al., 2024). Persistent compounds in these agents resist breakdown, which means they can contaminate rivers, lakes, and groundwater for extended periods, harming plants, animals (Mammadov et al.,2024), and humans (Lin et al., 2022) who rely on these water sources.

During conflicts, chemical agents like sarin (Petrea et al., 2018), mustard gas (Hosseini-khalili et al., 2009), and VX (Petrea et al., 2018) may leak or are purposefully released into the environment. Residues from these chemicals often remain on the surface or in soil and leach into nearby water bodies due to rain and groundwater movement (Levy and Sidel, 2016). These agents are designed to be toxic and can retain their harmful properties even after dispersal, meaning they can stay hazardous long after the initial exposure. The resulting pollution can affect rivers, lakes, and groundwater, harming aquatic ecosystems and making the water dangerous for human and animal consumption (Corredor et al., 2024).

Chemical warfare agents are often resistant to natural degradation, especially in colder or oxygen-poor environments, which are common in many water bodies. Mustard gas, for example, can persist in water, leading to prolonged exposure risks for both aquatic organisms and humans. Exposure to these agents can cause severe health effects, including skin burns, respiratory issues, and long-term illnesses. The stability and low degradation rate of these compounds make them particularly troublesome, as they can affect water quality over extended periods (EPA, 2011).

Certain chemical agents in water can bioaccumulate in aquatic organisms, moving up the food chain and becoming more concentrated in predators. This bioaccumulation is particularly concerning for larger animals, including humans, who rely on fish and other aquatic species for food. Exposure through bioaccumulation has been shown to cause reproductive, neurological, and developmental damage in animals and can pose similar risks to humans. For instance, contaminated fish consumed by humans can lead to the ingestion of hazardous chemicals, impacting health over time (Corredor et al., 2024).

When chemical agents start to break down, they often form secondary pollutants (Brzeziński et al., 2020), which may still be harmful or even more toxic than the parent compounds. For example, mustard gas degrades into toxic compounds that can further contaminate water, leading to a cycle of pollution that extends the hazard (Medvedeva et al., 2008). These by-products can be equally persistent, creating a complex challenge in treating and purifying affected water sources.

The health risks to humans from drinking or using contaminated water are substantial. Chemical agents like nerve toxins disrupt biological processes and can cause long-term health issues, including cancer, organ damage, and developmental effects on children exposed *in utero*. Furthermore, using such water for irrigation can transfer these contaminants into the soil and onto crops, broadening the contamination's impact on human health (Preethi and Subramani Thirumalaisamy, 2023).

Removing chemical weapon contaminants from water bodies is complex and resource-intensive. Techniques such as advanced oxidation, bioremediation, and activated carbon filtration have been used, but they are not universally effective against all agents. Remediation efforts also need to be maintained over time to address the continuous risk of residual contamination. Despite these efforts, complete removal remains challenging, and many sites

affected by chemical weapons remain hazardous for years or even decades after the initial contamination (EPA, 2011)

Explosives like TNT (2,4,6-trinitrotoluene) and RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) are commonly used in military applications. Both pose significant environmental risks when they contaminate water bodies during and after conflicts. These compounds can leach into water systems from unexploded ordnance, manufacturing sites, or disposal activities, leading to pollution that impacts aquatic ecosystems and human health.

3.2.2.1.1.1 TNT contamination and effects. TNT is toxic and does not degrade easily in natural environments, posing risks for long-term contamination. When TNT enters water bodies, it can undergo limited photodegradation, forming by-products like trinitrobenzene, which may also be harmful. However, TNT's persistence allows it to bioaccumulate in sediments and potentially enter the food chain, impacting aquatic organisms and even human populations consuming contaminated water. Chronic exposure to TNT has been linked to liver and blood disorders, reproductive issues, and potential carcinogenic effects. The U.S. Environmental Protection Agency (EPA) classifies TNT as a possible human carcinogen and has set strict guidelines for permissible levels in drinking water to limit its toxic impact (EPA, 2011; Corredor et al., 2024).

3.2.2.1.1.2 RDX Contamination and Effects. RDX, widely used in military munitions, is more water-soluble than TNT, making it more likely to spread in groundwater and surface water. It is toxic to aquatic organisms and, upon reaching drinking water sources, poses severe health risks, including potential nervous system and liver damage in humans. RDX contamination has been observed to disrupt microbial communities in water and soil, which hinders natural biodegradation processes. The compound is resistant to most natural degradation pathways, persisting in environments long after initial exposure (Corredor et al., 2024).

Both TNT and RDX have been subject to environmental and health concerns due to their persistence and toxicity. Research into bioremediation, including microbial and phytoremediation methods, is ongoing to address contamination by these explosives. However, current remediation technologies have limitations, and contamination from these compounds remains a significant ecological issue (EPA, 2011).

3.2.2.1.2 Oil spills and fires. Oil spills are a common environmental consequence of military actions, particularly in regions with oil-rich resources. During the Persian Gulf War, for instance, massive oil spills occurred when oil facilities were damaged and sabotaged, leading to contamination of the Persian Gulf and coastal areas (Linden et al., 2004). The fires from burning oil wells released hydrocarbons and other toxic compounds, which settled into marine and freshwater bodies, affecting fish, marine mammals, and birds. Oil residues in water have lasting impacts, disrupting photosynthesis in aquatic plants, reducing oxygen levels, and harming species that rely on clean water (Klem et al., 2017).

In addition to these specific incidents, the ongoing conflict in Gaza illustrates how warfare exacerbates environmental destruction through similar mechanisms. The relentless bombing has devastated agricultural lands and infrastructure, leading to significant ecological degradation. For example, prior to the conflict, northern Gaza was predominantly agricultural; however, it has since lost approximately 40% of its farmland due to military operations (Hassoun et al., 2024). This destruction not only impacts immediate landscapes but also disrupts local ecosystems and economies.

Moreover, the types of fires resulting from military actions can vary widely. Wildfires may be ignited by artillery strikes or incendiary weapons like white phosphorus, which have long-term health and environmental consequences. The contamination of soil and water sources with toxic substances further exacerbates the crisis in conflict zones like Gaza, where safe drinking water is increasingly scarce. The greenhouse gas emissions generated during military actions have been reported to exceed those of several climate-vulnerable nations combined, highlighting the far-reaching implications of warfare on global environmental health (World Health Organization (WHO), 2024).

The study "Conflict and Climate Drivers of Fire Activity in Syria in the Twenty-First Century," authored by Zubkova discusses how military actions and climate conditions contribute to fire incidents in conflict zones. The study highlights that fires can originate from both natural habitats and human activities, particularly in areas affected by war. It emphasizes that the arid climate in Syria makes ecosystems highly susceptible to fire, with armed conflicts often targeting agricultural lands, thereby exacerbating fire risks (Zubkova et al., 2021). According to the findings, fire affected 4.8% of Syria in 2019, a significant increase compared to the average of 0.2%, with most incidents occurring within agricultural areas in the northeast of the country.

Additionally, the research indicates that changes in fire activity are driven by a combination of natural and anthropogenic factors, including population growth, land management practices, and socioeconomic conditions (Bowman et al., 2011; Nikolić et al., 2023). This understanding is crucial for analyzing how military operations can disrupt natural fire regimes and lead to increased fire incidents.

3.2.2.2 Destruction of infrastructure

Destruction of water treatment plants, pipelines, and industrial facilities during warfare can lead to large-scale contamination of local water sources. For instance, in Iraq, the targeting of infrastructure has resulted in untreated sewage and industrial waste being discharged directly into rivers, such as the Tigris and Euphrates. This untreated waste introduces pathogens and chemicals into the water, endangering both the ecosystem and human health. In many conflict zones, broken infrastructure leads to long-term contamination and the inability of local communities to access safe drinking water (Gleick, 2014).

3.2.2.3 Radiological and nuclear contamination

The use or testing of nuclear weapons, as well as the targeting of nuclear facilities, has severe and long-lasting impacts on water quality. During the Cold War, nuclear testing introduced radioactive isotopes into the environment, contaminating water sources near test sites and affecting marine and freshwater life. In Ukraine, the 1986 Chernobyl nuclear disaster during a time of geopolitical tension released radioactive materials into surrounding rivers, leading to the contamination that persists decades later (Onishi, 2014). These contaminants pose serious

health risks as they accumulate in fish and other aquatic species, which can then enter human food supplies.

3.2.2.4 Impacts on aquatic ecosystems

3.2.2.4.1 Disruption of aquatic food chains. Contaminants introduced into water systems during conflict can significantly disrupt aquatic food chains, posing serious ecological and health risks. The presence of heavy metals and toxic chemicals, such as polychlorinated biphenyls (PCBs) and dioxins, is particularly concerning due to their ability to accumulate in the tissues of aquatic organisms through a process known as bioaccumulation (Yousif et al., 2021).

Bioaccumulation occurs when small organisms, such as algae and plankton, absorb these toxins from their environment. These contaminants can originate from various sources, including industrial runoff, military operations, and the disposal of chemical weapons, all of which can be exacerbated during times of conflict (Broomandi et al., 2020). Once absorbed, these toxins become increasingly concentrated as they move up the food chain.

As larger organisms consume smaller ones, the concentration of toxins magnifies at higher trophic levels. For instance, when fish eat contaminated plankton, they accumulate toxins in their bodies, which can reach dangerous levels over time (Khoshnood, 2017). This process is known as biomagnification. Predator species, such as larger fish, marine mammals, and birds, are particularly vulnerable to bioaccumulation because they consume large numbers of these contaminated organisms.

The effects of bioaccumulation can be severe. Predators that ingest these contaminated species can experience neurological damage, reproductive issues, and overall health (Brooks, 2015). In some cases, high levels of contaminants can lead to population declines, threatening the survival of entire species and disrupting the ecological balance within their habitats (Seren and Celekli, 2024). For example, studies have shown that certain bird species exposed to high levels of PCBs can suffer from reproductive failure and impaired immune function, leading to decreased population viability (Sara et al., 2020). Overall, introducing contaminants into aquatic systems during conflict not only jeopardizes the health of individual species but also disrupts entire ecosystems, with far-reaching consequences for biodiversity and human health.

For instance, in regions heavily impacted by military activities that have led to significant contamination of water systems, recovery efforts could focus on restoring natural habitats and implementing pollution remediation technologies. Engaging local communities in monitoring water quality and biodiversity can enhance recovery efforts while fostering stewardship over natural resources. Furthermore, integrating traditional ecological knowledge with scientific approaches may provide valuable insights into effective restoration practices that are culturally appropriate and sustainable (Haq eta al., 2023).

By prioritizing context-specific strategies that address both environmental restoration and community needs, it is possible to mitigate the long-term impacts of warfare on aquatic ecosystems.

3.2.2.4.1.1 Habitat destruction and loss of biodiversity. Military activities often result in significant habitat loss due to land use changes, deforestation, and urbanization. For instance, studies have shown that conflicts can lead to the degradation of forests and wetlands, which are critical for maintaining biodiversity (Fontaine, 2024).

Aquatic habitats, including wetlands, estuaries, and coral reefs, are crucial ecosystems providing numerous ecological services and supporting diverse life forms (Barbier et al., 2011). However, these habitats are highly sensitive to pollution, particularly war-related contaminants (Landrigan et al., 2020). The destruction of these habitats not only leads to the loss of biodiversity but also undermines the overall health and functionality of the ecosystem (van Dam et al., 2011).

Coral reefs are especially vulnerable to pollution, including oil spills, heavy metals, and agricultural runoff. Oil spills can suffocate coral reefs by forming a film on the water's surface, reducing light availability necessary for photosynthesis in symbiotic algae known as zooxanthellae, which provide energy to corals. When light diminishes, corals struggle to survive, leading to bleaching events where they expel these algae, resulting in a stark white appearance and increased vulnerability to disease (Hughes et al., 2017).

In freshwater habitats like rivers, lakes, and wetlands, the introduction of pollutants can devastate spawning grounds for many fish species. Excess nutrients from fertilizers can lead to algal blooms that deplete oxygen levels, creating dead zones where fish cannot survive (Diaz and Rosenberg, 2008). Additionally, heavy metals and toxic chemicals (Table 1) can impair reproductive cycles, affecting hormone levels and reducing egg viability (Singh et al., 2021).

The loss of biodiversity in these habitats has far-reaching consequences (Fontaine, 2024). Biodiversity contributes to ecosystem resilience, enabling them to withstand and recover from disturbances. Healthy ecosystems with high biodiversity are more resilient; however, pollution leading to biodiversity loss diminishes their ability to recover. This makes ecosystems more susceptible to further degradation, especially under ongoing stressors like climate change.

For instance, warming waters can exacerbate the impacts of pollution on already suffering coral reefs, potentially leading to a tipping point where recovery becomes nearly impossible (Administration, 2010; Ados Santos et al., 2015). In summary, aquatic habitats are critically endangered by pollution, particularly from war-related contaminants, leading to significant biodiversity loss that undermines ecosystem resilience and hampers recovery from other environmental stressors. Protecting and restoring these ecosystems is essential for maintaining biodiversity and ensuring the provision of vital ecosystem services. Conflicts disrupt local wildlife populations through habitat destruction and increased hunting or poaching activities. The loss of biodiversity reduces ecosystem resilience, making recovery more challenging.

3.2.2.4.1.2 Impact on drinking water and human health. The use of explosives and military vehicles introduces pollutants into the environment, affecting soil and water quality. Contaminants can persist long after conflicts end, posing long-term risks to both human health and ecological integrity (Fontaine, 2024). Contaminated water supplies are a significant risk to human populations in conflict zones, where clean water access is often limited or entirely unavailable. The presence of heavy metals,

pathogens, and various chemicals in drinking water can lead to severe health issues. For instance, exposure to heavy metals like lead and mercury can cause neurological damage, reproductive health problems, and increased cancer rates, especially concerning in areas where industrial and military activities have led to widespread contamination (Broomandi et al., 2020).

In war-torn regions, water infrastructure is frequently destroyed or left in disrepair, forcing displaced populations to rely on contaminated sources. This exacerbates public health crises, as inadequate sanitation leads to the spread of waterborne diseases such as cholera, dysentery, and typhoid fever. The breakdown of essential infrastructure means that populations in these areas have little to no means of ensuring safe water, intensifying the prevalence of diseases and long-term health risks (Gleick, 2014). These risks underscore the broader issue of environmental degradation in conflict zones, where pollutants from military operations, industrial runoff, and poorly disposed chemical materials create health hazards that could persist for years. Effective intervention requires immediate efforts to restore and secure water resources and infrastructure in these areas to reduce the public health burden on vulnerable populations (Gleick, 2014).

3.2.3 Impacts of war on soil

War can significantly contaminate soil with heavy metals, chemicals, and toxins from explosives and military activities. These pollutants can alter the soil's chemical composition, affecting its fertility and structure. Contaminated soil can lead to bioaccumulation in crops, meaning harmful substances may concentrate in food plants, ultimately entering the human food chain. This bioaccumulation poses serious health risks, including neurological disorders, reproductive issues, and various chronic diseases, particularly in communities that depend heavily on agriculture for sustenance (Leal Filho et al., 2024).

Military operations, including bombings and vehicle movements, physically disturb the soil, leading to compaction and increased erosion. The compaction reduces the soil's porosity, hindering water infiltration and root penetration, which affects plant growth. As vegetation is destroyed, the protective cover that prevents erosion is lost, resulting in the depletion of topsoil, which is crucial for nutrient retention and fertility. This degradation not only reduces agricultural yields but also exacerbates food insecurity in conflict-affected regions, making recovery difficult (Machlis et al., 2011).

The disruption of soil microbial communities due to pollutants is a significant consequence of war that profoundly affects soil health and ecosystem functioning. When heavy metals, chemicals from explosives, and other toxins infiltrate the soil, they create an inhospitable environment for beneficial microorganisms essential for nutrient cycling and organic matter decomposition. This disruption often leads to a decline in microbial diversity, crucial for maintaining soil resilience and fertility. A less diverse microbial community can hinder critical processes, such as nitrogen fixation and the breakdown of organic materials, leading to nutrient deficiencies that impact plant growth and agricultural productivity. Consequently, the degradation of soil health has severe implications for food security, particularly in conflict-affected regions, where populations are already vulnerable. The long-term effects of disrupted microbial communities further compromise ecosystem resilience, making soils more susceptible to erosion and contamination, thereby creating a cycle of environmental degradation that can persist long after hostilities have ceased (Machlis et al., 2011; Brauer, 2016).

In regions where war has led to significant soil degradation and contamination, tailored recovery strategies are essential. These strategies should consider local socio-economic conditions and resource availability to ensure effective restoration of soil health. For example, integrating sustainable agricultural practices that enhance soil quality while addressing immediate food security needs can be beneficial (Emurotu and Onianwa, 2017). Additionally, involving local communities in recovery efforts can foster stewardship over natural resources while providing education on sustainable land management practices that mitigate further degradation.

3.2.4 Impacts of war on air

The impacts of warfare on air quality are profound and multifaceted, as evidenced by both historical and contemporary conflicts. The Gulf War of 1991 serves as a critical case study due to the extensive oil fires ignited by Iraqi forces, which released massive amounts of pollutants into the atmosphere (Zalakeviciute et al., 2022).

A study by Smith et al. (2020) found that during the Gulf War, emissions of SOx increased by approximately 50% in affected areas due to the burning of oil wells, leading to severe air pollution that impacted both local populations and ecosystems (Smith et al., 2020). Over 600 oil wells were set ablaze, emitting significant quantities of carbon monoxide, sulfur dioxide, and nitrogen oxides, leading to severe air pollution across the region (Lange et al., 2002). This resulted in phenomena such as "black rain," where carbon-laden particles were deposited hundreds of miles away, affecting countries like Iran and Turkey. The environmental consequences were dire, compromising soil and air quality and adversely impacting health and agricultural productivity in the region (Roberts, 1992; Linden et al., 2004; Harari and Annesi-Maesano, 2023).

In more recent conflicts, such as the Ukraine war, similar patterns have emerged. Damage to industrial facilities and energy infrastructure has led to significant pollutant releases. For instance, the destruction of the Kakhovka dam in June 2023 resulted in heavy contamination from fuel oils (Zalakeviciute et al., 2022; Meng et al., 2023). Additionally, shelling-induced fires have exacerbated air pollution by releasing hazardous chemicals and particulates, heightening health risks, particularly respiratory issues (Harari and Annesi-Maesano, 2023; Leal Filho et al., 2024).

Warfare often targets infrastructure critical to industrial operations, leading to the release of toxic chemicals into the atmosphere. During the Iraq War, for example, damage to chemical facilities resulted in dangerous leaks that contributed to regional air pollution. The release of hazardous air pollutants (HAPs) from these sites poses long-term environmental threats due to the persistence of many pollutants in the atmosphere (Ross, 1992; Malarvizhi et al., 2023). Moreover, military operations themselves generate substantial emissions from vehicles and aircraft, contributing significantly to greenhouse gas emissions. The U.S. Department of Defense is one of the largest institutional emitters globally, with military fuel consumption

exacerbating existing environmental vulnerabilities (Lange et al., 2002; Meng et al., 2023).

The interplay between resource scarcity, climate change, military maneuvers, and conflict is increasingly evident in contemporary warfare. As natural resources become scarcer due to climate change impacts, competition for these resources can intensify conflicts. This competition may lead to more aggressive military strategies that further degrade air quality through increased emissions from military activities and the destruction of industrial infrastructure (Zalakeviciute et al., 2022; Meng et al., 2023). Additionally, the environmental degradation caused by warfare can create a vicious cycle where compromised ecosystems exacerbate resource scarcity, fueling further conflict.

The ongoing Ukraine war exemplifies this trend: as military operations continue amidst a backdrop of climate change-induced resource scarcity, the resulting air pollution not only poses immediate health risks but also contributes to long-term environmental degradation that can destabilize regions further (Meng et al., 2023; Leal Filho et al., 2024). This highlights an urgent need for integrated approaches that consider environmental impacts in conflict resolution and military strategy formulation.

3.2.5 Impact of war on protected areas

Approximately 20% of protected areas in Ukraine have been significantly affected by the ongoing war, with military actions impacting around 812 protected areas totaling nearly one million hectares. This includes the occupation of eight nature reserves and ten national parks, which poses a substantial risk to important wildlife sites. Notably, 2.9 million hectares of the Emerald Network are at risk, highlighting the potential loss of vital habitats that are part of Europe's nature conservation framework. Additionally, 16 Ramsar sites, covering over 600,000 ha, are under threat of destruction due to military activities. These sites are recognized for their unique biodiversity and international importance as wetlands (Leal Filho et al., 2024).

3.2.5.1 Impacts of war as a causal of climate change

The connection between war and climate change is evident both during and after conflicts. During active military operations, immediate impacts include habitat destruction and direct emissions from military actions. For instance, military operations such as bombing campaigns and troop movements directly destroy critical ecosystems like forests, wetlands, and grasslands, which play vital roles in carbon sequestration and regulating water cycles (Kim and Garcia, 2023). This obliteration releases stored carbon back into the atmosphere, exacerbating global warming.

Increased greenhouse gas emissions (GHGs) resulting from military operations contribute significantly to environmental pollution and climate change. Approximately 5.5% of global greenhouse gas emissions are generated by military activities worldwide. This includes emissions from fuel consumption, equipment production, and operational activities (Neimark, 2024).

War leads to significant destruction of ecosystems, resulting in severe land degradation and biodiversity loss. Directly, military operations such as bombing and troop movements obliterate critical habitats like forests and wetlands, which play essential roles in carbon sequestration and water cycles (Kim and Garcia, 2023). The resulting land clearing and infrastructure development disrupt local ecosystems, leading to soil compaction and pollution from fuel spills and toxic substances (Baumann and Kuemmerle, 2016).

In addition to immediate destruction, the effects of war on climate change are also evident in the post-conflict phase. After wars, the land often undergoes significant changes in use patterns—shifting from agricultural or natural lands to military zones (Forsyth and Schomerus, 2013). This shift can lead to habitat fragmentation and increased poaching due to weakened law enforcement, further diminishing biodiversity (Ummah, 2022). Moreover, conflicts can introduce invasive species that outcompete native flora and fauna, disrupting local ecosystems (Boucher et al., 2013). The destruction of infrastructure during conflicts such as oil refineries and pipelines results in oil spills and gas leaks that release significant quantities of greenhouse gases into the atmosphere (Gassan-zade, 2024).

Research indicates that the emissions generated during conflicts can be substantial. For example, the Russian invasion of Ukraine produced more greenhouse gas emissions in its first year than the entire Czech Republic did in the same period (Klerk, 2022). The cumulative impact of land degradation and biodiversity loss from war underscores the need for integrating environmental considerations into conflict resolution and post-conflict recovery strategies.

To estimate these effects comprehensively, researchers utilize several methodologies. Life cycle assessment (LCA) evaluates the environmental impacts associated with all stages of a military operation from resource extraction through production, operation, and disposal quantifying both direct emissions from fuel consumption and indirect emissions from equipment production. Remote sensing technology allows researchers to visualize habitat destruction and changes in vegetation cover before, during, and after conflicts. Ecosystem service valuation assesses the economic value of ecosystem services lost due to military operations. Health impact assessments quantify long-term health effects on populations exposed to military-related pollution. Comparative studies further isolate specific environmental impacts attributable to military actions by comparing regions affected by war with similar regions that have not experienced conflict (Stuart Parkinson, 2022).

To effectively address these challenges, it is essential to implement actionable policy measures such as international monitoring systems for environmental impacts during conflicts, mandatory environmental impact assessments for military actions before their execution, and economic incentives for post-war restoration efforts. These measures can help ensure that environmental considerations are prioritized alongside military objectives. By understanding both the immediate and long-term effects of military actions on ecosystems and greenhouse gas emissions, policymakers can better address these challenges in conflict-affected regions.

Healthy ecosystems are crucial for carbon sequestration; their destruction not only releases stored carbon but also reduces future absorption capacity (Griscom et al., 2017). Therefore, promoting ecological restoration is essential for sustainability and mitigating climate change.

TABLE 1 Toxic chemicals Emitted by war equipment and their Environmental Impact.

Type of military equipment	Toxic chemicals emitted by equipment	Environmental impact of toxicants emitted by war equipment
Tanks (T-55, T-72) (Cahyanti, 2016)	NOx, SO_2 Chlorine gas Cahyanti (2016)	NOx, SO_2 gases emitted from tanks contribute to acid rain and degrade the environment, especially in areas with high deployment levels. These gases react with moisture in the atmosphere, forming acidic compounds that can harm soil, water, and vegetation, ultimately impacting ecosystems Likens, (2018), Prakash et al. (2023) During warfare, chlorine gas emissions from tanks can lead to serious environmental damage. This chlorine exposure contaminates soil, harming health and microbial life Parakhnenko et al. (2023). Additionally, chlorine gas can dissolve in water bodies, leading to water pollution that endangers aquatic ecosystems and poses health risks to communities depending on these water sources Cahyanti (2016) The movement of tanks can compact soil and disrupt local flora and fauna, leading to long-term ecological changes Lawrence et al. (2015) In desert environments, tracked vehicles like tanks can cause significant sediment loss and alter microtopography, which affects vegetation recovery and soil stability Fuchs et al. (2003) Military activities significantly contribute to environmental degradation, particularly by relying on tanks and heavy machinery emitting toxic chemicals that adversely affect local ecosystems. These emissions stem from various military operations, including training exercises and warfare, introducing potentially toxic elements (PTEs) and energetic compounds (ECs) into the environment. The consequences are especially pronounced in ecologically sensitive areas, where military presence has led to substantial ecological damage, threatening biodiversity and disrupting the natural balance of these regions Broomandi et al. (2020), Dey and Basu (2023) Soil contamination with PTEs such as lead results from military activities, leading to increased erosion and reduced soil fertility Broomandi et al. (2020) Additionally, the use of ammunition and explosives releases toxic compounds that can affect both immediate areas and distant ecosystems through air and water transport Petrea et al. (2018). The cumulative impact of these military operations underscores the urgent need for awareness and mitigation strategies to address the environmental consequences of military activities
Armored Vehicles (BMP, BTR)	NOx, SO_2 Explosives Wisniewski and Pirszel (2021) TNT and RDX Lotufo et al. (2019)	NOx, SO_2 released armored vehicles contribute to environmental degradation and acid rain, particularly in regions with heavy military presence. When these gases interact with atmospheric moisture, they form acidic compounds that can harm soil, water bodies, and plant life, leading to broader ecology Likens (2018), Prakash et al. (2023) The weight of armored vehicles can compact soil, reducing its porosity and leading to erosion, particularly in sensitive ecosystems Wisniewski and Pirszel (2021) Explosives used can introduce harmful chemicals into the soil, affecting microbial communities and plant growth Wisniewski and Pirszel (2021) Explosives and vehicle maintenance fluids can leach into nearby water bodies, degrading water quality and harming aquatic life The movement of these vehicles can disturb sediments, releasing trapped pollutants into the water TNT and RDX substances from armored vehicles can leach into water bodies due to corrosion or breaches in munitions, posing risks to aquatic ecosystems Lotufo et al. (2019) The long-term ecological impacts include changes in soil composition, disruption of microbial communities essential for ecosystem health, and contamination of water sources affecting both wildlife and human health Akhundov (2024b)

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TABLE 1 (*Continued*) Toxic chemicals Emitted by war equipment and their Environmental Impact.

Type of military equipment	Toxic chemicals emitted by equipment	Environmental impact of toxicants emitted by war equipment
Artillery (D-30 Howitzers)	Phosgene	Military activities, including artillery operations, can introduce chemical warfare agents, such as phosgene, into the environment, causing chemical disruptions. These agents can alter soil chemistry, harm microbial communities essential for soil health, and pose risks to water quality by leaching into groundwater or surface water. This contamination can impact both aquatic ecosystems and human drinking water supplies, creating broader ecological and health hazards Broomandi et al., (2020), Parakhnenko et al. (2023) The long-term environmental consequences of emissions significantly impact both terrestrial and aquatic ecosystems, leading to alterations in biodiversity, ecosystem health, and overall ecological balance. These emissions introduce pollutants that can cause oxidative stress and bioaccumulation of toxic substances, affecting various organisms and their habitats. In terrestrial ecosystems, acidifying pollutants, heavy metals such as mercury, and nitrogen compounds alter soil chemistry and plant physiology (Wright et al., 2018), resulting in biodiversity loss as changes in plant species composition and growth rates lead to habitat degradation that affects wildlife populations (Wright et al., 2018). Increased pollutant levels also contribute to oxidative stress in flora, diminishing their resilience to environmental changes (Kerchev and Van Breusegem, 2022). In aquatic ecosystems, pollutants like mercury convert to methylmercury, which bioaccumulates in aquatic food chains, posing significant risks to fish and marine birds (Wright et al., 2018). Moreover, alterations in these ecosystems disrupt carbon fixation processes, leading to reduced carbon storage capabilities (Fan Yang, 2024). Overall, the cumulative effects of these emissions underscore the urgent need for effective environmental management strategies to mitigate their impact on both terrestrial and aquatic systems
Aircraft (MiG-29, Su-25)	Mustard gas CO_2 CO, NO_x SO_x, HCs, PM. These emissions contribute to air pollution, and the NO_x gases, in particular, can lead to acid rain and smog formation Oh et al. (2008)	Military aircraft emissions like NO_x contribute to the depletion of the ozone layer and introduce pollutants into the atmosphere, affecting air quality at various altitudes Andreas Asbjornsen and Paragiri (1992) Aircraft like the MiG-29 and Su-25 emit various gases due to the combustion of jet fuel, primarily including CO_2, CO, NO_x, SO_x), unburned HCs, and PM. These emissions contribute to air pollution, and the NO_x gases, and, in particular, can lead to acid rain and smog formation, furthermore, emissions like CO_2, which is a major greenhouse gas can cause global warming and impact both human health and the environment Oh et al. (2008) Military activities, including the use of chemical agents, lead to significant soil contamination. Mustard gas, for instance, poses long-term risks due to its persistence and toxicity Broomandi et al. (2020) The introduction of potentially toxic elements (PTEs) and chemical warfare agents can alter soil properties, leading to increased erosion and other environmental issues Broomandi et al. (2020) "Aircraft emissions account for approximately 1.3% of total ozone formation and 0.2% of PM2.5 concentrations at the surface, with more pronounced effects observed in Europe Vennam, et al. (2018). Emissions at cruise altitudes are primarily responsible for odd nitrogen and ozone perturbations near the ground Lee et al. (2009). Furthermore, aircraft emissions are estimated to account for about 13% of total surface global warming, significantly affecting Arctic warming and cloud formation Jarošová and Pajdlhauser (2022).These emissions lead to increased atmospheric stability, altering cloud dynamics and contributing to climate change Jarošová and Pajdlhauser (2022)

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TABLE 1 (*Continued*) Toxic chemicals Emitted by war equipment and their Environmental Impact.

Type of military equipment	Toxic chemicals emitted by equipment	Environmental impact of toxicants emitted by war equipment
Drones	VOCs, NOx, CO, PM from jet fuel or combustion engines. When armed, drones may also release residues from explosive materials such as TNT or RDX, and sometimes toxic heavy metals like lead or cadmium, depending on the types of munitions used	NOx and SO_2 gases emitted from drones contribute to acid rain and environmental degradation, especially in areas of heavy deployment Increased drone usage in urban and industrial areas can elevate local concentrations of these pollutants, exacerbating acid rain formation Acid rain can lower soil pH, leading to nutrient leaching and harming forest ecosystems, particularly in sensitive regions Kozłowski et al. (2011) Acid deposition negatively impacts freshwater bodies, affecting aquatic life and water quality Visgilio et al. (2007) Toxic residues from military activities, including drone operations, can lead to soil and water pollution, affecting local agriculture and drinking water sources Cristaldi et al. (2013) The introduction of toxic chemicals can disrupt local ecosystems, leading to declines in species populations and biodiversity Lawrence et al. (2015) Drones contribute to air pollution through emissions from their combustion engines, similar to traditional aircraft, which release CO, NOx, and PM. Gardner (2015) Emissions from drones contribute to poor air quality, with pollutants exceeding legal limits, which can have long-term health effects on nearby populations Cristaldi et al. (2013) The introduction of toxic chemicals can disrupt local ecosystems, leading to declines in species populations and biodiversity Lawrence et al. (2015)
Missile and rocket propellants	Hydrazine and its derivatives, particularly unsymmetrical dimethylhydrazine (UDMH)	Rocket stages fueled by UDMH have been discarded in ecologically sensitive areas, leading to contamination of marine environments Byers and Byers (20017) Hydrazine can irreparably damage aquatic ecosystems and soil health, affecting flora and fauna Hydrazine, due to its high toxicity and good water solubility, can cause significant environmental damage, contaminating air and water bodies. This contamination poses potential risks to ecosystems Zhang and Cheng (2023); Xia et al. (2024) The disposal of rocket propellants in ecologically sensitive areas raises serious environmental concerns that require urgent attention Al-Mohanna and Subrahmanyam (2001)

In the 2022 report launched as a contribution to the COP27climate negotiations, and in collaboration with the Conflict and Environment Observatory (CEOBS) the global military carbon footprint is estimated to be approximately 2,750 million tonnes of CO_2 equivalent, accounting for about 5.5% of global emissions, with significant contributions from supply chain emissions and resource consumption during production processes (Bar et al., 2023; Parkinson, 2023).

Historical data shows that when military activity slows, there is a notable drop in emissions, highlighting demilitarization's potential role in reducing carbon outputs. The environmental benefits of decreased military operations suggest that the global push for decarbonization could be significantly advanced by reducing the frequency or intensity of military exercises and operations. These insights underscore the broader environmental impacts of military sectors worldwide and suggest that peace and sustainability goals could be aligned to yield substantial ecological benefits (Parkinson, 2023).

The military's dependency on fossil fuels for a range of activities from transportation to power generation makes it one of the largest institutional sources of greenhouse gases. However, the lack of consistent reporting on military emissions hinders a clear understanding of their full environmental impact, contributing to a significant knowledge gap. Scholars like Ahmad (2024) and Neimark (2024) emphasize that without transparency in military carbon accounting, efforts to address climate change are incomplete. Addressing these emissions requires systemic changes to improve accountability, alongside an international commitment to assess and manage military-related environmental costs (Ahmad, 2024; Neimark, 2024).

Table 2) provides a comprehensive overview of the relationship between the consumption of raw materials in military equipment production and the associated greenhouse gas emissions. It highlights how increased resource use correlates with higher emissions, shedding light on the environmental impact of military manufacturing. For instance, steel, essential for constructing tanks and ships, accounted for approximately 733 million tons produced during World War II, resulting in significant CO_2 emissions due to the energy-intensive nature of steel manufacturing. Similarly, crude oil consumption reached

TABLE 2 Environmental impacts of military operations: production, operation, and post-operation effects.

Phase	Description	Environmental component affected	References
Production	Involves high resource consumption, including metals and hydrocarbon manufacturing of military equipment	Soil and water contamination from mining; significant greenhouse gas emissions associated with military production facilities; it is estimated that militaries contribute approximately 5.5% of global GHG emissions	Vuong et al. (2024)
Pre-war contamination	Environmental degradation begins with military buildup and training activities	Land and water contamination from military training exercises; habitat disruption; and emissions from vehicles and facilities	Vuong et al. (2024)
Operation	Use of military vehicles and weaponry during conflicts	Air pollution from fuel combustion; soil degradation from vehicle movement; and water pollution from munitions and explosives. The environmental health impacts of military operations, particularly in Ukraine, have led to increased air pollution levels due to bombings and destruction of fuel storage facilities	Leal Filho et al. (2024)
Post-Operation	Cleanup and remediation efforts following military conflicts	Soil and groundwater contamination from unexploded ordnance; challenges in restoring ecosystems affected by military activities	Qumsiyeh (2024)
Long-Term Effects	Lasting impacts on ecosystems due to military activities, including chemical residues and habitat changes	Persistent contamination in soils and water bodies; biodiversity loss; increased deforestation rates as communities return to land	Hryhorczuk et al. (2024), Qumsiyeh (2024)

around 1.043 billion tons during the same period, with its combustion contributing notably to greenhouse gas emissions (Thunder Said Energy, 2022). Aluminum, utilized extensively in aircraft and lightweight vehicles, also has a considerable environmental footprint, with 5.1 million tons produced during WWII and high emissions from its smelting process.

In contemporary contexts, modern military equipment incorporates advanced materials such as electronics and composites, with resource consumption varying by country and technology. This increased production complexity leads to higher emissions. Additionally, resource extraction for metals and minerals often results in environmental degradation and pollution, further contributing to greenhouse gas emissions from mining operations. Overall military production reflects the cumulative impact of global military expenditures on resource consumption and emissions, which are expected to rise as nations modernize their military capabilities in response to geopolitical tensions. Understanding this correlation is crucial for policymakers and defense contractors as it can inform strategies to reduce military operations' carbon footprint. Potential measures include investing in cleaner technologies, implementing recycling programs for materials like steel and aluminum, and exploring alternative energy sources to decrease reliance on fossil fuels. By addressing these issues, the military sector can work towards minimizing its environmental impact while maintaining operational effectiveness.

3.3 Long-term environmental effects

The long-term impacts of military technologies extend far beyond the immediate ecological damage caused during active conflicts. One significant concern is legacy pollution. Areas that have been used for military training or combat often become sites of persistent environmental contamination. This legacy pollution can result from a range of pollutants, including heavy metals, unexploded ordnance, and toxic chemicals used in munitions and military operations. Such contaminants can remain in the soil, water, and air long after military activities have ceased, creating ongoing risks for human health and local ecosystems. Communities near former military sites may face increased health risks due to exposure to these pollutants, which can lead to serious illnesses and hinder the restoration of the affected areas (Lawrence et al., 2015).

In addition to legacy pollution, military operations contribute significantly to climate change. The military sector is heavily reliant on fossil fuels for its operations, leading to substantial greenhouse gas emissions. From the logistics of transporting troops and equipment to the energy-intensive nature of military exercises, the carbon footprint of the military is considerable. While the increased use of drones might offer some reductions in emissions when compared to traditional aircraft, this benefit is often overshadowed by the overall impact of military activities. Drones may be more efficient, but they are still part of a broader system that relies on fossil fuels and contributes to climate change (Park et al., 2018; Federal Aviation Administration, 2024).

To measure the long-term effects of Agent Orange during the Vietnam War, researchers employed various statistical methods including regression analysis and instrumental variable approaches to assess health outcomes in populations exposed to dioxins compared to unexposed groups. For example, studies have shown that individuals living in areas with higher dioxin exposure experienced significantly higher rates of cancer and other health issues decades after exposure (Olson and Morton, 2019). Furthermore, comparisons between the environmental impacts observed during the Vietnam War and those from recent conflicts in Iraq and Afghanistan reveal similar patterns of contamination and health risks associated with military operations (Akhundov, 2024a). In Iraq, for instance, tactics such as oil well fires set by retreating forces during the Gulf War resulted in massive air pollution and long-term ecological damage similar to that seen in Vietnam due to Agent Orange (Davis, 2020). Additionally, modern conflicts continue to demonstrate deliberate environmental destruction as a tactic of war, further complicating recovery efforts in affected regions (CEOBS, 2020).

The cumulative effects of military technologies, therefore, present a complex challenge while they may enhance operational

effectiveness and efficiency in certain contexts, they also leave a lasting negative legacy that affects both environmental health and climate stability. Addressing these impacts requires a comprehensive approach, including pollution remediation efforts and a shift toward more sustainable practices within military operations. As resource consumption increases (e.g., steel, oil, aluminum), associated emissions also tend to rise due to the energy-intensive nature of production processes (Table 2). The trend of rising military expenditures globally suggests a potential increase in resource consumption and emissions, necessitating further analysis for sustainable practices in military production.

4 International case law on ecocide

4.1 The vietnam war and agent orange

One of the earliest instances that brought attention to the concept of ecocide was during the Vietnam War when the U.S. military's use of Agent Orange resulted in extensive environmental damage and health issues for local populations (Boucher, 2011). Although no formal charges were brought under an ecocide framework, this case highlighted the environmental consequences of military actions and laid the groundwork for future discussions on legal accountability for environmental destruction in conflict zones (Sziebig, 2024).

The extensive use of Agent Orange not only devastated ecosystems but also prompted a reevaluation of military strategies and their long-term impacts on the environment. Understanding these historical precedents can guide contemporary military operations to prioritize environmental considerations, ensuring that similar mistakes are not repeated. For instance, integrating environmental impact assessments into military planning can help mitigate ecological damage before it occurs.

The Vietnam War serves as a critical case study in recognizing the importance of protecting natural resources during armed conflict. By analyzing past failures and successes, modern militaries can develop policies that promote sustainable practices, such as minimizing chemical usage and employing alternative strategies that reduce ecological footprints (Zierler, 2011). This historical awareness is essential for establishing frameworks that hold military actors accountable for their environmental impacts and for fostering a culture of responsibility towards ecological preservation in conflict situations.

4.2 The 2018 UN report on environmental law

The United Nations has recognized gaps in international environmental law regarding accountability for severe environmental harm (Voigt, 2021). The 2018 UN Report identified the fragmented nature of existing laws and called for a comprehensive legal framework to address issues like ecocide. This report serves as a precursor to ongoing discussions about establishing legal definitions and frameworks for prosecuting ecocide (Kovalenko et al., 2024).

4.3 Recent developments in ecocide law

4.3.1 Proposed amendments to the Rome Statute

In June 2021, an Independent Expert Panel proposed amendments to the Rome Statute to formally include ecocide as a fifth international crime. This proposal aims to create a robust legal basis for prosecuting individuals responsible for significant environmental harm (van Trigt, 2021). The proposed definition focuses on acts that cause severe ecological damage, emphasizing the need for accountability beyond traditional war crimes.

4.3.2 National legislation examples

In recent years, several countries have taken important steps in establishing national laws to address "ecocide," signaling a shift in how states perceive and respond to severe environmental degradation (Ejeromedoghene et al.,2021). These legal frameworks seek to prosecute and punish those who cause substantial ecological harm, and they represent a significant development in both environmental and human rights law (Nurse, 2017). This movement is especially relevant in the context of a review of the impact of war on the environment, where the concept of ecocide has profound implications for holding individuals and entities accountable for environmental damage caused during conflicts.

4.3.2.1 France: climate & resilience act

France's Climate & Resilience Act introduces robust provisions to address environmental offenses, specifically targeting severe ecological damage (Jousseaume, 2022). Passed in 2021, this legislation allows for the prosecution of those responsible for substantial environmental harm, with penalties reaching up to 10 years of imprisonment and substantial fines. This Act represents a major step toward recognizing environmental degradation as a serious criminal offense, signaling France's commitment to protecting ecosystems. Notably, while the law applies broadly, its implications extend to wartime activities that might result in massive ecological damage. France's legislative efforts indicate an increasing acknowledgment of the need for national policies to address ecocide, aligning with the evolving global conversation on environmental justice.

4.3.2.2 Ecuador: article 245 of the penal code

In Ecuador, Article 245 of the Penal Code criminalizes "crimes against the environment," embodying a nationwide stance against ecological harm (Tigre, 2013). Ecuador has been a pioneer in environmental protection, notably enshrining the Rights of Nature in its Constitution in 2008, which grants ecosystems legal standing and intrinsic rights. This legal framework is especially relevant in addressing wartime environmental destruction, as Ecuador's Penal Code explicitly criminalizes actions compromising ecosystems' integrity (Swing et al., 2022). By embedding environmental protection into its penal system, Ecuador sets a powerful example for integrating ecocide legislation into domestic law. The criminalization of environmental destruction in Ecuador underscores a national commitment to addressing and preventing ecological harm, whether during peacetime or in the wake of conflict-related activities.

4.3.2.3 Vietnam: article 278 of the penal code

Vietnam's Article 278 of the Penal Code identifies ecocide as a crime against humanity, highlighting the nation's progressive stance on environmental protection (Chiarini, 2022). This provision is unique in that it explicitly addresses ecocide within both peace and wartime contexts, marking it as a crime with severe consequences regardless of the circumstances. Vietnam's legislation aligns closely with international principles, recognizing that environmental destruction can lead to catastrophic and long-lasting effects on communities and ecosystems (Tín, 2019). By treating ecocide as a crime against humanity, Vietnam's approach represents a forward-thinking model that acknowledges the inextricable link between human rights and environmental protection. For conflicts where environmental damage is often severe and enduring, such legislation sets a precedent for addressing ecocide as a serious, punishable offense under national law.

4.4 National laws on ecocide and influence on international norms

The emergence of national laws in countries like France, Ecuador, and Vietnam to criminalize ecocide reflects an increasing recognition of severe environmental destruction as a matter warranting legal accountability (Arifin et al., 2024). The impact of such laws on the international stage cannot be underestimated; these legislative measures serve as potential blueprints for other countries and may eventually influence international norms and standards (Foyet et al., 2024). As more countries adopt laws addressing ecocide, the cumulative effect may create a legal environment where international treaties and conventions incorporate ecocide as a recognized crime. In the context of war and conflict, the growing support for ecocide legislation could lead to heightened protections for the environment and stricter accountability measures for environmental harm in wartime, moving closer to international recognition of ecocide as a crime under international law (Chiarini, 2022).

By exploring the national laws of countries that address ecocide, this review highlights the significant role of domestic legal systems in shaping global environmental governance. Through these laws, France, Ecuador, and Vietnam demonstrate a proactive approach to tackling ecological harm, setting an important precedent for global policy on wartime environmental protection and justice.

4.5 Implications for future prosecutions

The growing recognition of ecocide as a serious crime carries substantial implications for future prosecutions, especially within the context of environmental harm in war zones. The potential establishment of ecocide as an internationally recognized crime would reshape legal, corporate, and environmental practices by extending accountability, enhancing corporate responsibility, and encouraging preventive measures (Arifin et al., 2024).

4.6 Legal accountability

Designating ecocide as an international crime would create a legal framework to prosecute individuals and entities responsible for significant environmental destruction, particularly in conflict situations. Currently, international law focuses on war crimes, crimes against humanity, and genocide, often overlooking environmental devastation that might occur during armed conflicts (Kovalenko et al., 2024). Including ecocide in the list of prosecutable international crimes would allow for the prosecution of military leaders, political figures, and others responsible for ecological harm during wartime. This shift could lead to heightened accountability, where those causing extensive environmental destruction such as scorched-earth tactics or targeting critical ecosystems are held liable, aligning environmental damage with other serious wartime offenses (Kovalenko et al., 2024; Sziebig, 2024).

4.7 Corporate responsibility

The inclusion of ecocide in legal frameworks could also bring corporations under scrutiny. Presently, international law mainly holds individuals accountable, with limited mechanisms to address corporate activities that lead to significant environmental harm. If ecocide were recognized as an international crime, corporate entities involved in extractive industries, chemical production, or other environmentally destructive operations could face legal consequences (Zierler, 2022). This would mark a transformative change in how corporations approach ecological responsibility, particularly those operating in conflict-affected areas (Ruggie, 2011). By extending accountability to companies, ecocide legislation would encourage more sustainable practices, as corporations would need to mitigate environmental risks to avoid legal repercussions (Bilchitz and Deva, 2011).

5 Challenges ahead

The movement toward recognizing ecocide as a crime faces several substantial challenges that could impact its implementation and enforcement on an international scale. Although the recognition of ecocide has gained traction, there are significant obstacles to making it a universally accepted and enforceable law. Key challenges include the lack of consensus on a definition, political hurdles, and practical implementation issues.

5.1 Lack of consensus

A major challenge in establishing ecocide as an international crime is the absence of a universally accepted definition and framework for prosecution. Ecocide currently lacks a clear, cohesive legal definition that is accepted by all nations, leading to inconsistencies in how it is understood and enforced. Some countries, like Vietnam and Ecuador, have included ecocide within their national laws, yet they each interpret it differently (Sterio, 2024).

Without a standardized definition, international enforcement becomes problematic, as what qualifies as ecocide in one jurisdiction might not be recognized as such in another. Achieving consensus on a definition will require input from environmental scientists, legal experts, and policymakers worldwide to ensure the term captures both the scale of ecological harm and its impacts on communities (Puleo, 2021).

Furthermore, the complexities surrounding the legal interpretation of ecocide highlight the need for a robust framework that addresses these disparities and facilitates international cooperation. As noted by Palarczyk (2023), without a clear legal basis, efforts to prosecute ecocide could face significant challenges within existing judicial systems (Palarczyk, 2023).

5.2 Political will

For ecocide laws to be widely adopted, significant political will and public support are essential. Implementing ecocide as an international crime requires countries to agree on and adopt these laws within their national legal systems, which can be a lengthy and complex process (Sterio, 2024). Nations with powerful industrial lobbies or those heavily reliant on natural resource extraction may resist ecocide legislation due to fears of economic impact and restrictive regulatory requirements. Additionally, political leaders may hesitate to back ecocide laws if they believe it could limit their countries' development goals or be used to target certain industries. To overcome this challenge, advocates of ecocide legislation must work to build public awareness and political support by demonstrating the long-term environmental, social, and economic benefits of protecting ecosystems (Puleo, 2021).

5.3 Implementation issues

Even with a consensus and political support, effective implementation remains a considerable hurdle. Prosecuting ecocide requires judicial systems to handle complex cases that involve scientific evidence, environmental data, and expert testimony, all of which demand specialized knowledge and resources (EUFJE, 2019). Many legal systems may not be equipped to manage these cases, as they typically lack the technical expertise required to assess the scale and impact of environmental destruction. In countries with limited judicial resources or high levels of corruption, enforcing ecocide laws becomes even more challenging. For ecocide laws to be practically enforceable, there will need to be significant investments in judicial training, environmental monitoring, and forensic resources, as well as mechanisms to support cross-border cooperation in cases involving transnational environmental harm (Palarczyk, 2023).

5.4 Practical barriers

Addressing practical real-world barriers to prosecuting ecocide is crucial for its successful implementation. These barriers include political resistance from nations that rely heavily on natural resource extraction or have influential industrial lobbies opposing stricter environmental regulations. Additionally, enforcement mechanisms can be weak or nonexistent in many jurisdictions due to inadequate funding or a lack of trained personnel within judicial systems capable of handling complex environmental cases (Ruggie, 2020a). Overcoming these barriers will require concerted efforts from international organizations and NGOs to provide support for capacity-building initiatives aimed at strengthening local legal frameworks.

5.5 Path forward

Addressing these challenges will require a multi-faceted approach that includes collaboration, capacity-building, and advocacy. To overcome the lack of consensus, the international community could establish a standardized legal framework for ecocide, potentially through organizations like the United Nations or the International Criminal Court (ICC) (Palarczyk, 2023). Building political will might involve public awareness campaigns, showcasing the human and environmental costs of unchecked ecological harm, and engaging leaders who support environmental justice (Ruggie, 2020b). Finally, overcoming implementation challenges will necessitate investing in judicial infrastructure, creating expert panels, and developing environmental crime units within law enforcement agencies (Puleo, 2021).

In summary, while the recognition of ecocide as a crime presents a promising path forward for environmental protection, significant challenges remain. Addressing these obstacles will require coordinated global efforts to create a universally accepted legal definition, mobilize political support, and equip judicial systems to effectively handle cases of ecocide. If these challenges can be met, ecocide could become a powerful legal tool for safeguarding ecosystems, particularly in conflict zones where environmental harm often goes unpunished.

6 Mitigation strategies

Mitigation strategies are increasingly being developed to address the environmental impacts associated with military technologies. One important approach involves the adoption of sustainable practices within military operations. Some armed forces are exploring the use of renewable energy sources, such as solar and wind power, to operate drones and other equipment, thereby reducing reliance on fossil fuels. Additionally, militaries are implementing stricter environmental management policies during training exercises to minimize disturbances to local ecosystems. These practices may include conducting training activities in designated areas that are less ecologically sensitive, employing techniques that limit habitat disruption, and ensuring the proper disposal of waste generated during exercises (Federal Aviation Administration, 2024).

Another crucial element of mitigation is the use of environmental assessments as part of regulatory frameworks. In the United States, for instance, the National Environmental Policy

Act (NEPA) mandates that federal agencies, including the military, conduct environmental assessments for proposed actions that could significantly affect the environment. These assessments are designed to evaluate the potential adverse impacts of military operations, including those involving drones, and identify measures to minimize harm to ecosystems. By requiring comprehensive evaluations before military actions are undertaken, NEPA aims to promote informed decision-making and ensure that environmental considerations are integrated into military planning and operations (Federal Aviation Administration, 2024).

Recognizing ecocide as an international crime could drive nations to adopt stricter environmental protections and sustainable practices, acting as a deterrent against potential ecological disasters. By establishing clear legal consequences for ecological harm, ecocide legislation may encourage countries to strengthen domestic environmental policies and regulations, especially in resource extraction, military operations, and conflict zones (Ruggie, 2011). Nations might invest more in preventive strategies, such as conducting environmental impact assessments, protecting critical habitats, and developing sustainable resource management plans to minimize the likelihood of ecocide. This preventive approach would not only help to preserve ecosystems during times of peace but also limit environmental degradation during conflicts, fostering a culture of ecological stewardship (Minkova, 2024). The criminalization of ecocide is seen as a necessary extension of legal protections for the environment, particularly in peacetime situations where current laws may not adequately address severe ecological harm (Moribe et al., 2023). As countries recognize the need for accountability in environmental destruction, the integration of ecocide into international law could significantly enhance enforcement mechanisms and promote a global standard for ecological responsibility (Mwanza, 2022). This shift would encourage nations to adopt comprehensive legal frameworks that prioritize environmental health and sustainability, ultimately contributing to preserving biodiversity and ecosystem integrity.

To mitigate environmental impacts in post-conflict settings, a range of tailored strategies can be implemented, emphasizing sustainable rebuilding policies (Hasic, 2004). Armed conflicts often lead to significant environmental damage through various mechanisms, including the destruction of ecosystems, resource depletion, and pollution. Military activities can devastate forests, wetlands, and wildlife habitats, disrupting biodiversity. Additionally, conflicts result in the over-exploitation of natural resources like timber and water, leading to long-term ecological consequences. The use of chemical weapons and munitions contaminates land and water sources, posing serious health risks to local populations. These impacts create a cycle of degradation that can exacerbate tensions and lead to renewed conflict over scarce resources if not effectively addressed.

Sustainable Rebuilding Policies are essential in this context. Key strategies include.

6.1 Green building practices

Prioritizing environmentally friendly construction methods significantly reduces ecological footprints. This involves using sustainable materials, energy-efficient designs, and waste-minimization techniques during rebuilding efforts (Hasic, 2004).

6.2 The SCOPE model

This model emphasizes a multidisciplinary approach to post-conflict reconstruction by integrating various sustainable practices into rebuilding efforts. It encourages collaboration among stakeholders governments, NGOs, and local communities to ensure that environmental considerations are central to recovery strategies (Easterday and Ivanhoe, 2017).

6.3 Strategic environmental assessments (SEAs)

Conducting SEAs is crucial for identifying potential environmental risks associated with reconstruction projects. These assessments help decision-makers understand how proposed developments may impact ecosystems and human health, allowing for informed planning that prioritizes sustainability (Network and Environment, 2010).

6.4 Community engagement

Involving local communities in decision-making processes fosters ownership and enhances the effectiveness of environmental policies. Community-based initiatives can lead to more sustainable practices that are tailored to local contexts and needs (Zwijnenburg, 2021).

6.5 Capacity building

Strengthening the capacity of local institutions to manage natural resources sustainably is vital. This includes training programs focused on environmental management and governance that empower communities to take an active role in their recovery (Sandra, 2011).

Monitoring and Evaluation is essential for the success of post-conflict environmental initiatives. Establishing robust monitoring systems allows stakeholders to continuously assess the effectiveness of funded projects, creating a vital feedback loop that enables the adaptation of strategies as needed and ensures accountability in the use of resources (United Nations Environment Programme UNEP, 2009). Additionally, Collaborative Environmental Monitoring plays a crucial role in this process by engaging local communities in monitoring environmental conditions. This engagement not only ensures transparency but also promotes sustainable practices. By involving local populations, this approach helps build local capacities and fosters a sense of ownership over environmental stewardship initiatives, ultimately enhancing the effectiveness and sustainability of recovery efforts (Uwiringiyimana and Gitahi, 2022).

Implementing these strategies within a framework that recognizes the interconnections between environmental health and social stability, post-conflict regions can work towards

sustainable recovery while minimizing the risk of future conflicts driven by resource scarcity.

6.5.1 International environmental aid mechanisms

Establishing international funding programs dedicated to environmental restoration in conflict-affected regions can support recovery efforts. The United Nations Development Programme outlines a framework for inclusive planning and financing that accelerates sustainable reconstruction, particularly in urban areas impacted by crises (UNDP, 2023).

6.6 The need for international environmental aid mechanisms

Conflict-affected regions often face compounded challenges due to environmental degradation, which exacerbates humanitarian crises. The interplay between climate change and conflict creates a vicious cycle where environmental damage leads to resource scarcity, further fueling tensions and instability. For instance, the International Committee of the Red Cross (ICRC) highlights that climate change disproportionately affects countries in conflict, making recovery efforts even more challenging.

6.7 Framework for inclusive planning and financing

The UNDP's framework emphasizes several key components essential for effective international environmental aid mechanisms.

6.7.1 Multilateral funding initiatives

Establishing dedicated funding programs through multilateral organizations can ensure that resources are allocated specifically for environmental restoration. These funds can support projects aimed at rebuilding infrastructure, restoring ecosystems, and enhancing community resilience (FAO, 2021).

6.7.2 Technical assistance and capacity building

Providing technical expertise and training to local governments and communities is vital for implementing sustainable practices. This includes developing skills in environmental management, sustainable agriculture, and disaster risk reduction (Ministry of Local Government, 2013).

6.7.3 Community engagement

Involving local populations in the planning and implementation of environmental restoration projects fosters ownership and ensures that initiatives meet the specific needs of affected communities. Engaging stakeholders helps build trust and enhances the effectiveness of recovery efforts (Mendgen, 2024).

6.7.4 Integrated approaches

The framework advocates for integrated planning that considers social, economic, and environmental factors. This holistic approach ensures that reconstruction efforts not only address immediate needs but also promote long-term sustainability (UNEP, 2019).

6.7.5 Monitoring and evaluation

This is essential for the success of post-conflict environmental initiatives. Establishing robust monitoring systems allows stakeholders to continuously assess the effectiveness of funded projects, creating a vital feedback loop that enables the adaptation of strategies as needed and ensures accountability in the use of resources (Uwiringiyimana and Gitahi, 2022). Additionally, Collaborative Environmental monitoring plays a crucial role in this process by engaging local communities in monitoring environmental conditions. This engagement not only ensures transparency but also promotes sustainable practices. By involving local populations, this approach helps build local capacities and fosters a sense of ownership over environmental stewardship initiatives, ultimately enhancing the effectiveness and sustainability of recovery efforts (World Bank Group, 2020).

6.8 Recent developments in environmental assistance

The recent resolution passed during the sixth UN Environment Assembly (UNEA-6) underscores the growing recognition of the need for environmental assistance in conflict-affected areas (UNEA-6, 2024). This resolution aims to enhance the United Nations Environment Programme's (UNEP) responsiveness to the environmental dimensions of armed conflicts. It calls for developing technical guidance on measuring environmental damage, which can inform recovery strategies and support funding initiatives.

7 The way forward: addressing ecocide and the environmental impact of war

As conflicts increase globally, the urgent need to address ecocide and the severe environmental destruction resulting from warfare becomes critical. War has devastating consequences on ecosystems, biodiversity, and human health, often leaving lasting damage that can take decades to recover from. Here is a comprehensive approach to mitigate these impacts, incorporating legal, collaborative, restorative, and educational strategies to address and prevent ecocide effectively.

7.1 Establishing legal frameworks for ecocide

7.1.1 International recognition

Recognizing ecocide as an international crime under the Rome Statute of the International Criminal Court (ICC) would empower global institutions to hold individuals and entities accountable for environmental destruction during conflicts. By formally defining ecocide alongside crimes like genocide and war crimes, the international community can establish clear standards and consequences for ecological harm in war zones (Sterio, 2024). Amending the Rome Statute would require support from ICC member states, but this step is essential to building global consensus and deterrence. The proposed definition of ecocide

emphasizes unlawful or wanton acts committed with the knowledge that there is a substantial likelihood of severe and either widespread or long-term damage to the environment (Group of Experts, 2021). This amendment would not only enhance legal accountability but also align with the growing recognition of environmental protection as a critical aspect of international law.

7.1.2 National legislation

Countries should implement national laws criminalizing ecocide, as exemplified by France's Climate & Resilience Act (Kovalenko et al., 2024). This law creates a legal foundation for prosecuting those responsible for ecological destruction, extending liability to both individuals and corporations involved in environmentally harmful activities. Article 280 of the Climate & Resilience Act establishes punitive measures for "ecocide" crimes when infringements result in serious and lasting damage to health, flora, fauna, or the quality of air, soil, or water (Arifin et al., 2024). National ecocide laws could also complement international frameworks by providing local jurisdictions with the authority to pursue cases and deter potential offenders.

7.2 Strengthening international cooperation

7.2.1 Global agreements

To protect ecosystems from wartime destruction, countries should work together to create binding international agreements, building on existing frameworks like the Geneva Conventions. Enhanced protocols could specify protections for natural resources and fragile ecosystems during armed conflict, ensuring that environmental protection becomes a core component of international humanitarian law (IRRC, 2023).

7.2.2 Cross-border initiatives

Environmental impacts from war often affect neighboring countries. Establishing cross-border initiatives, such as joint environmental assessments and restoration projects, allows countries to address the shared consequences of conflict. These initiatives could include collaborative pollution cleanup efforts, shared resource management, and coordinated policies to rehabilitate impacted ecosystems (Dorsouma and Bouchard, 2023).

7.3 Enhancing environmental assessments and monitoring

7.3.1 Post-conflict environmental assessments

Standardizing post-conflict environmental assessments would provide accurate information on the damage inflicted upon ecosystems, wildlife, and human health. These assessments could serve as foundational tools for formulating long-term recovery strategies and prioritizing areas most impacted by war. They would also document the environmental costs of conflict, potentially serving as evidence in future ecocide cases (Hryhorczuk et al., 2024; Leal Filho et al., 2024).

7.3.2 Real-time monitoring

Utilizing advanced monitoring technologies, such as satellite imagery and remote sensing, allows for the real-time tracking of environmental changes during conflicts. This data can help assess the immediate impact of war on natural resources and biodiversity, guiding humanitarian interventions and providing crucial information for post-conflict restoration efforts (Zwijnenburg et al., 2020; Tomchenko, et al., 2023).

7.4 Promoting sustainable recovery practices

7.4.1 Ecological restoration

Post-conflict recovery efforts should emphasize ecological restoration. This could include reforestation, habitat rehabilitation, and pollution removal, all aimed at restoring damaged ecosystems and promoting biodiversity recovery. Involving local communities in these efforts not only strengthens social resilience but also ensures that restoration aligns with the needs and knowledge of those directly affected (Quiroga et al., 2024). Biodiversity recovery is essential as it enhances ecosystem functioning, which provides critical services such as clean air and water, soil fertility, and resilience to climate change (Matta et al., 2011; Sachini wayanthimali et al., 2021). Healthy ecosystems can better withstand disturbances, thus promoting long-term sustainability for communities recovering from conflict (Hobbs and Harris, 2001).

7.4.2 Integrating environmental considerations in reconstruction

Reconstruction after conflict should be informed by principles of environmental sustainability. This means prioritizing eco-friendly materials and practices, reducing carbon footprints, and planning for long-term ecological (Hobbs and Harris, 2001). Sustainable reconstruction promotes resilience against future conflicts and environmental challenges (Adebayo, 2024). By integrating biodiversity considerations into reconstruction efforts, we can ensure that ecosystems are not only restored but also enhanced to support diverse species and improve overall ecosystem services. This holistic approach fosters a sustainable relationship between communities and their environment, ultimately contributing to peacebuilding efforts and reducing the likelihood of future conflicts driven by resource scarcity (Cheng and Li, 2024).

7.5 Raising awareness and education

7.5.1 Public awareness campaigns

Educating the public, policymakers, and military personnel about the environmental impact of war is essential to fostering a culture of accountability. Public campaigns highlighting the ecological damage associated with conflicts can help build support for ecocide legislation and sustainable recovery practices. Awareness can drive demand for more stringent environmental protections, both in times of peace and conflict (Bothe, 2023; Sziebig, 2024).

7.5.2 Training for military personnel

Incorporating environmental considerations into military training would prepare armed forces to make more ecologically conscious decisions during operations. This training could cover topics like minimizing environmental footprints in combat zones, protecting water sources, and avoiding actions that lead to widespread habitat destruction (Smit, 2020; Tolochko et al., 2022).

7.6 Fostering research and development

7.6.1 Research funding

Allocating funding for research on the environmental impacts of war is crucial to understanding and mitigating these effects. Research on historical and current conflicts can inform future policies and offer insights into best practices for rehabilitation. This knowledge can guide strategies that prioritize ecological health and resilience during conflict recovery (Qumsiyeh, 2024; Tarkhani, 2024).

7.6.2 Innovative solutions

Encouraging innovation in military technology that minimizes environmental harm would contribute to reducing the ecological footprint of armed conflicts. This could include developing less harmful munitions, creating methods that preserve habitats, or finding alternatives to resource-intensive military practices (Zwijnenburg et al., 2020; Tarkhani, 2024). Investing in these solutions not only protects the environment but also aligns with the broader goals of sustainable development.

Generally, to effectively address the environmental impact of war and prevent ecocide, a comprehensive approach is necessary. This includes creating robust legal frameworks, fostering international cooperation, promoting ecological restoration, and raising awareness through education and training. Research and innovation are also essential for developing solutions that minimize the environmental toll of military operations. By prioritizing these strategies, the international community can protect ecosystems during conflicts, promote sustainable recovery, and establish a pathway toward greater ecological accountability and justice.

8 Conclusion

In conclusion, the environmental impacts of war represent a significant yet often overlooked aspect of the conflict, manifesting in profound ecological destruction and contributing to the phenomenon of ecocide. Armed conflict not only leads to the immediate destruction of ecosystems through bombing, deforestation, and pollution but also results in the long-term degradation of biodiversity and natural resources. The military's extensive reliance on fossil fuels exacerbates greenhouse gas emissions, further accelerating climate change and destabilizing affected regions. Additionally, the disruption of local governance and environmental policies during conflicts hinders recovery efforts and compromises sustainable practices.

This research is important because it highlights the critical interplay between warfare and ecological degradation, emphasizing that the consequences of conflict extend far beyond human casualties to include lasting damage to our planet's ecosystems. New findings from our study reveal that approximately 20% of protected areas in Ukraine have been negatively impacted by the ongoing war, leading to significant chemical contamination and habitat destruction.

Recognizing the intricate link between war and environmental degradation is essential for informing conflict resolution strategies, promoting peace, and fostering sustainable development. To mitigate the environmental consequences of war, it is crucial to integrate ecological considerations into military operations, enhance post-conflict recovery efforts, and prioritize conservation initiatives in vulnerable areas. Addressing the environmental dimensions of conflict is a vital component of creating a more sustainable and peaceful future; however, it must be part of a broader strategy that includes social, economic, and political considerations to ensure comprehensive solutions and accountability for those responsible for ecocide.

By expanding our understanding of these issues, we can better advocate for policies that protect both people and the environment in times of conflict.

Author contributions

YW: Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. UA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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