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Warfare Practices and Experiments and Their Effects on the Environment

Chokri Zehri
Department of Finance, College of Business Administration in Hawtat Bani Tamim, Prince Sattam Bin Abdulaziz University, Saudi Arabia.
c.alzhari@psau.edu.sa

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Abstract

War and armed conflict have devastating impacts not only on human populations but also on the environment. This paper explores various warfare practices, violations of international humanitarian law, and their immediate and long-term environmental consequences. Using an ARDL model, we analyze data from 1990 to 2023 across 19 wars and military conflicts to assess their ecological impact. Our study examines deforestation, soil degradation, water contamination, air pollution, and biodiversity loss. We find that conflict intensity and duration have the most significant influence on ecological damage, while displacement and refugee numbers play a relatively minor role. The analysis shows that economic factors do not contribute to environmental harm. Additionally, the long-term effects of war and conflict are more pronounced than short-term impacts. Based on these findings, we recommend that policymakers prioritize the integration of comprehensive environmental protection measures in conflict resolution strategies. This includes implementing strict regulations against environmentally harmful practices during warfare, promoting sustainable development initiatives in post-conflict reconstruction, and fostering international cooperation to address the ecological impacts of conflicts.
Keywords: *International humanitarian law, wars, environment, conflict, ecological, experiments*

1. Introduction

In recent years, there has been a growing debate on the environmental consequences of wars and military conflicts, as the global community becomes increasingly aware of the profound and often irreversible damage inflicted on ecosystems during and after conflicts (Lawrence et al., 2015; Certini et al., 2013). These discussions have highlighted the need to understand not just the immediate humanitarian impact of war but also its long-term environmental fallout, particularly in the context of the violation of international humanitarian law.

Many cases highlight the long-lasting and far-reaching environmental impacts of war, which extend beyond immediate conflict zones and continue to affect ecosystems and human populations for years to come. Recent conflicts worldwide have led to significant ecological deterioration, underscoring the severe ecological consequences of war (Jayasinghe, 2024; Elasha, 2014). In Yemen, the ongoing conflict has intensified the country's water crisis, with the destruction of infrastructure leading to water contamination and depletion of groundwater resources. In Syria, widespread deforestation and agricultural collapse have resulted from the civil war, as people resort to cutting down trees for fuel and bombing has ravaged fertile lands. The Iraq War saw extensive oil spills and fires, particularly in the southern marshlands, causing air pollution and soil contamination (Kevlihan, 2013; Leaning, 2002). The conflict in Ukraine has led to industrial pollution and uncontrolled forest fires, further harming ecosystems. In Afghanistan, prolonged warfare has contributed to land degradation, with abandoned agricultural lands repurposed for poppy cultivation, exacerbating soil erosion and loss of arable land.

Although the environmental consequences of warfare practices and experiments are often visually evident—ranging from deforestation and water contamination to air pollution and soil degradation—a notable lack of empirical studies establishes a clear causal-effect linkage between these conflicts and ecological deterioration. Most discussions have focused on the observable damage, but systematic, data-driven analyses that quantify and confirm the direct impacts of warfare on ecosystems remain scarce (Solokha et al., 2023). This gap in research limits our understanding of the full extent of environmental harm caused by war, underscoring the need for empirical studies that can provide concrete evidence of these causal relationships.

This paper contributes to the ongoing debate and addresses this research gap by presenting an empirical analysis of the causal relationship between warfare, including violations of international humanitarian law, and environmental degradation. By employing an ARDL model, the study quantifies the impact of warfare practices and experiments on key ecological indicators, providing robust, data-driven insights. This analysis is intended to inform and shape policy discussions regarding the environmental costs of armed conflict, highlighting the need for more comprehensive approaches in global environmental and security policies (Ide, 2020).

Our empirical model examines the evolution of four key ecological deterioration indicators—deforestation rates, biodiversity loss, pollution levels, and land degradation indices—during 19 warfare practices, experiments, and cross-country conflicts between 1990 and 2023. We reveal several critical insights into the environmental impacts of armed conflicts. Firstly, the intensity and duration of conflicts emerge as the primary drivers of environmental degradation. High-intensity conflicts often lead to widespread destruction of ecosystems, pollution of air and water resources, and long-lasting damage to biodiversity (Limaj et al., 2023). The extended duration of such conflicts exacerbates these effects, allowing environmental harm to accumulate over time and making recovery increasingly difficult.

In contrast, the displacement of populations and the rise in refugee numbers, while significant humanitarian concerns, appear to have a comparatively minor impact on ecological deterioration. Although the movement of large populations can lead to localized environmental pressures, such as deforestation and resource depletion in refugee camps, these effects are less pronounced than those caused directly by the conflict's violence and infrastructure damage (Schon, 2020).

Interestingly, our findings suggest that economic factors, often considered influential in environmental outcomes, do not play a significant role in conflict-driven environmental deterioration. This could be due to the overriding influence of direct conflict-related activities, which overshadow any economic dynamics that might otherwise affect the environment (Cowdrey, 1983).

Moreover, the long-term impacts of warfare practices and experiments are considerably more substantial than their short-term effects. The environmental consequences of conflicts often persist for years or even decades after hostilities cease, as damaged ecosystems struggle to recover and land and water remain contaminated (Drachuk et al., 2024). This highlights the enduring legacy of conflicts on the environment, underscoring the need for sustained post-conflict environmental restoration efforts.

The paper is structured as follows: Section 2 presents a literature review on the environmental impact of warfare practices and experiments. Section 3 describes the data, variables, and empirical methodology used in the study. Section 4 displays the empirical results and their interpretation. Section 5 discusses policy implications and provides recommendations to mitigate the adverse effects of wars on the environment. The final section concludes the paper.

2. Literature review

The literature on the environmental effects of war practices provides a multifaceted exploration of how military activities impact ecosystems, biodiversity, pollution levels, and human health (Meaza et al., 2024; Jayasinghe, 2024; Buheji and Al-Muhannadi, 2023; Limaj et al., 2024; Van der Vet, 2024; Lawrence et al., 2015). It examines the ecological consequences of warfare, highlighting habitat destruction, deforestation, soil degradation, and disruptions to wildlife populations caused by combat operations, military infrastructure, and the use of weaponry. Scholars also investigate the release of pollutants and hazardous materials, including from conventional and unconventional weapons, which contaminate soil, water sources, and the air, posing long-term risks to environmental and human health (Wenning and Tomasi, 2023). Discussions often encompass the loss of biodiversity, habitat fragmentation, and the indirect impacts on ecosystems, emphasizing the importance of preserving vulnerable environments affected by conflict (Drachuk et al., 2023).

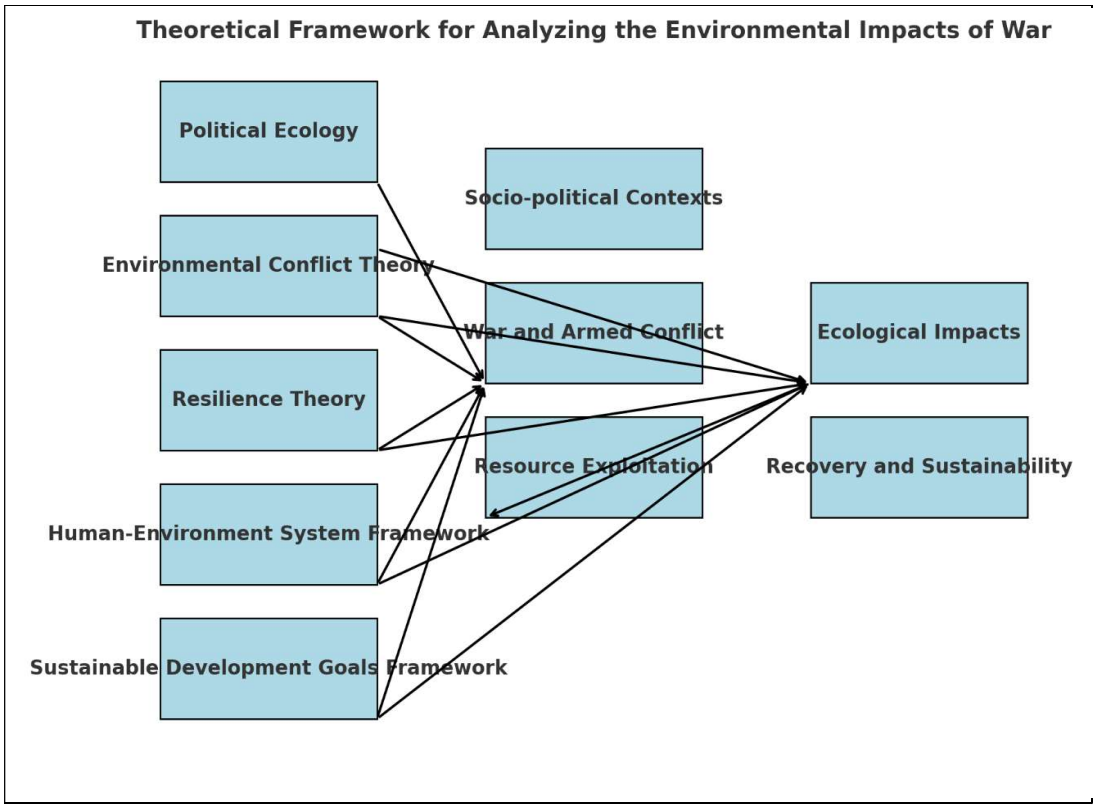

Figure 1. Theoretical framework

Theoretically, as detailed in Figure 1, our study is grounded in the model proposed by Homer (1994), which the following equation can summarize:

$$E = \alpha W^2 + \beta D + \gamma P^{-1} - \delta E + \epsilon R(D^{-1}) \qquad \text{Eq. (1)}$$

Where E denotes ecological damage, W represents war intensity, D reflects war duration, and P signifies political and governance factors. This model is particularly relevant to our study, which explores the devastating impacts of war and armed conflict on the environment, examining various warfare practices and violations of international humanitarian law. It effectively captures the critical influences of war intensity and duration, which we found to be significant

determinants of ecological harm, as well as the role of governance in mitigating such damage. Additionally, the recovery component emphasizes the need to understand how ecosystems recover post-conflict, aligning with our analysis of immediate and long-term environmental consequences such as deforestation, soil degradation, water contamination, air pollution, and biodiversity loss. Overall, this model provides a robust theoretical framework for analyzing the intricate relationships between warfare and environmental degradation, reinforcing the importance of addressing ecological impacts in discussions of armed conflict.

Moreover, the literature reviews humanitarian and health impacts, exploring how environmental degradation exacerbates humanitarian crises, contributes to displacement, food insecurity, and increases vulnerability to natural disasters in conflict-affected regions (Nikolaychuk, 2022; Ide, 2020). Policy and management responses are also a focus, assessing international legal frameworks, environmental treaties, and military practices to mitigate environmental harm during and after conflicts (Solokha et al., 2023; Drožđek et al., 2020; Sylvester, 2012). This includes evaluating the effectiveness of cleanup and rehabilitation efforts, promoting sustainable military practices, and advocating for stronger environmental protections in warfare. Overall, this body of research underscores the need for integrated approaches to address the environmental dimensions of warfare, aiming to inform policy, foster international cooperation, and promote resilience-building and sustainable development in post-conflict recovery (Lawrence et al., 2015; McSorley, 2013; Leaning, 2002).

Armed conflicts can have significant and enduring environmental effects (Meaza et al., 2024). Their adverse effects can be severe and widespread, ranging from eradicated forests and other habitats to polluted soil and water. The disruption of environmental management systems and the inability to access natural resources can also harm people's and the environment's health. Therefore, exploring and comprehending the impact of ongoing armed conflicts on the environment and the regional ecosystems is essential (Certini et al., 2013).

The impact of armed conflicts on the environment, exemplified by cases such as Sudan and Syria, reveals profound and multifaceted ecological deterioration exacerbated by prolonged warfare and resource mismanagement. In Sudan, conflicts over natural resources like oil and agricultural lands have led to severe environmental problems such as desertification, deforestation, and water scarcity (Elasha, 2014; Cowdrey, 1983). The destruction of infrastructure and contamination of water sources have worsened humanitarian conditions, contributing to diseases and widespread poverty. Efforts to mitigate these impacts, including international support for infrastructure restoration and local environmental management programs, highlight initiatives to preserve and restore ecosystems amidst conflict (Austin and Bruch, 2000).

Similarly, the Syrian conflict has inflicted extensive environmental damage, with the use of explosives and hazardous materials contaminating groundwater and causing habitat loss (Schon, 2020; Karaca, 2018). Population displacement has strained natural resources, leading to overexploitation of water and forests, exacerbating biodiversity loss and wildlife trafficking. Illegal logging for makeshift camps has further depleted Syria's forests, illustrating the compounding environmental toll of conflict. Addressing these challenges requires integrating environmental considerations into conflict resolution and reconstruction efforts, emphasizing research and community empowerment to develop sustainable environmental management strategies amidst ongoing instability and resource scarcity. Despite the formidable obstacles, prioritizing environmental protection in conflict zones remains essential for long-term resilience and sustainable development (Schon, 2020; Karaca, 2018).

3. Data and Empirical methodology

Studying the implications of warfare practices and experiments on environmental deterioration necessitates a strategic approach in selecting a representative sample of wars and cross-country conflicts. This involves identifying specific conflicts that have demonstrated varying intensities and durations to provide a comprehensive analysis. Additionally, it is crucial to define the types of environmental deterioration under scrutiny, such as deforestation, soil degradation, and water contamination, to ensure a focused examination of how different aspects of warfare contribute to ecological damage. The following Table reports the sample used in our study, highlighting significant wars and cross-country conflicts between 1990 and 2023.

Table 1. Sample of wars and cross-country conflicts

Conflict	Years	Countries Involved	Main Causes
Gulf War (First Iraq War)	1990-1991	Iraq vs. Kuwait + Coalition Forces (led by the USA)	Iraq's invasion of Kuwait
Bosnian War	1992-1995	Bosnia and Herzegovina, Croatia, Serbia	Ethnic tensions following the breakup of Yugoslavia
Rwandan Civil War	1990-1994	Rwanda (RPF vs. Government Forces)	Ethnic tensions between Hutus and Tutsis
First Chechen War	1994-1996	Russia vs. Chechnya	Chechnya's bid for independence from Russia
Second Congo War (Great African War)	1998-2003	DRC + 9 African countries	Ethnic conflicts, control over resources
Kosovo War	1998-1999	FR Yugoslavia vs. NATO + Kosovo Albanian Forces	Ethnic tensions, Kosovo's quest for independence
Second Chechen War	1999-2009	Russia vs. Chechen Rebels	Control over Chechnya
War in Afghanistan	2001-2021	USA + NATO vs. Taliban	Response to 9/11 attacks, regime change
Iraq War (Second Iraq War)	2003-2011	USA + Coalition vs. Iraq	Alleged WMDs, regime change
Russo-Georgian War	2008	Russia vs. Georgia	Control over South Ossetia and Abkhazia
Gaza War (Operation Cast Lead)	2008-2009	Israel vs. Hamas (Gaza)	Conflict over Gaza, rocket attacks, blockades
Libyan Civil War (First)	2011	Libyan Government vs. Rebels + NATO	Arab Spring, anti-Gaddafi uprising
Syrian Civil War	2011-present	Syria vs. Various rebel groups + ISIS + Foreign Powers	Anti-government protests, regime change
Russo-Ukrainian War	2014-present	Russia vs. Ukraine + International Involvement	Annexation of Crimea, control over Donbas region
Saudi-led Intervention in Yemen	2015-present	Saudi Arabia + Coalition vs. Houthi Rebels	Political instability, control over Yemen
Nagorno-Karabakh Conflict	2020	Armenia vs. Azerbaijan	Territorial dispute over Nagorno-Karabakh
Tigray War	2020-2022	Ethiopia + Eritrea vs. Tigray Region	Political tensions, autonomy demands
Russo-Ukrainian War (Full-Scale)	2022-present	Russia vs. Ukraine + Western Allies	Invasion of Ukraine, territorial disputes
Armenia-Azerbaijan Border Clashes	2022-present	Armenia vs. Azerbaijan	Ongoing tensions post-Nagorno-Karabakh war

Note: This Table covers major conflicts; many other smaller or less-known conflicts also occurred during this period.
Source: author presentation from Uppsala Conflict Data Program

The sample of wars and cross-country conflicts presented in the Table 1 covers a diverse range of geopolitical regions, causes, and durations. These conflicts span from the early 1990s to the present, involving various countries and coalitions. They are characterized by complex

motivations, including ethnic tensions, territorial disputes, political instability, and responses to international terrorism.

The conflicts outlined in the Table illustrate the profound linkage between warfare and environmental degradation, as each has contributed to significant ecological harm. For instance, the Gulf War saw the deliberate destruction of oil wells in Kuwait, leading to widespread oil spills and air pollution that devastated marine and terrestrial ecosystems. Similarly, the Bosnian War and the Rwandan Civil War resulted in massive deforestation and land degradation as displaced populations cleared forests for survival, exacerbating soil erosion and loss of biodiversity. In the Second Congo War, the exploitation of natural resources by armed groups led to the extensive destruction of wildlife habitats and the overexploitation of forests, further driving environmental decline. The Syrian Civil War has caused extensive damage to agricultural lands and water resources, as infrastructure targeting and the displacement of millions have led to overuse and contamination of limited resources. The prolonged nature of the War in Afghanistan has also left a lasting impact on the environment, with deforestation for fuel, destruction of irrigation systems, and pollution from military activities contributing to long-term environmental degradation. These examples demonstrate how conflicts disrupt human lives and inflict severe and lasting damage on the environment, further complicating post-conflict recovery and sustainable development efforts.

Turning to types of environmental deterioration, Figure 2 illustrates the primary environmental impacts of wars, highlighting significant issues such as deforestation, biodiversity loss, pollution levels, and land degradation. Wars often lead to widespread deforestation as forests are cleared for military activities or displaced populations seek resources. This destruction of natural habitats contributes to severe biodiversity loss, with countless species driven to extinction or pushed to the brink due to habitat disruption and hunting. Pollution levels also rise sharply in conflict zones, with chemicals, explosives, and waste contaminating air, water, and soil. Additionally, land degradation is exacerbated by destroying agricultural areas, infrastructure, and ecosystems, leaving the land scarred and less productive, further hindering post-conflict recovery and sustainability. Our empirical model will utilize these four key environmental impacts—deforestation, biodiversity loss, pollution levels, and land degradation—as our dependent variables. These variables will allow us to quantitatively assess the extent to which wars contribute to environmental degradation.

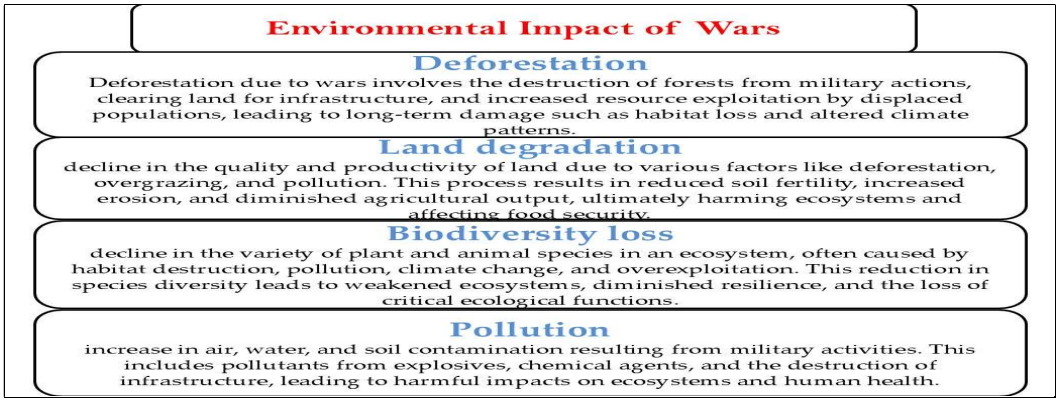

Figure 2. Primary Environmental Impacts of warfare practices and experiments

To examine the impact of conflict-related factors on environmental degradation using a panel ARDL model. This model allows you to analyze both the long-run and short-run effects of

conflict-related factors on environmental degradation while controlling for economic, demographic, and pre-conflict environmental conditions. We define four different dependent variables to assess ecological degradation:

- DEFi,t: Deforestation rates, measured in hectares per year.
- BIOi,t: Biodiversity loss, measured as species richness or abundance.
- POLLi,t: Pollution levels, including water, air, and soil contaminants.
- LANDi,t: Land degradation indices, such as soil erosion rates.

To capture the implications of wars and cross-country conflicts, our model includes three conflict-related factors:

- ICi,t: Intensity of conflict, measured by battle-related deaths.
- DCi,t: Duration of conflict, measured in years.
- DRNi,t: Displacement and refugee numbers, representing the number of people displaced internally or seeking refuge in other countries due to conflict.

We control for economic factors by including gross domestic product (GDP), poverty rates (POV), and inflation rates (INF), as these variables may influence environmental conditions. Additionally, we include a variable measuring pre-conflict ecological conditions (PCEC) to assess environmental changes. We use data from the Global Environmental Monitoring System (GEMS), managed by the United Nations Environment Programme (UNEP). GEMS provides historical data on various environmental indicators, including air and water quality, which helps establish the environmental baseline before conflicts. Tables 2 and 3 in the appendices describe all variables used in the study and their corresponding descriptive statistics, respectively.

The panel ARDL model is expressed as follows:

$$Y_{it} = \alpha_i + \lambda_t + \beta_0 X_{it} + \beta_1 Z_{it} + \gamma_1 \Delta X_{it} + \gamma_2 \Delta Z_{it} + \epsilon_{it}$$

where:

- Y_{it} represents the dependent environmental impact indicators (Deforestation, Biodiversity loss, Pollution levels, Land degradation indices),
- X_{it} represents the conflict-related factors (Conflict Intensity, Conflict Duration, Displacement and refugee numbers),
- Z_{it} represents the control variables (GDP, Poverty rates, Population Density, Pre-conflict Environmental Conditions),
- α_i denotes country-specific fixed effects,
- λ_t denotes time-specific effects,
- Δ represents the first difference operator,
- β_0 and β_1 are the long-run coefficients of the independent and control variables, respectively,
- γ_1 and γ_2 are the short-run coefficients of the independent and control variables, respectively,
- ϵ_{it} is the error term.

4. Results and interpretation

The results presented in Table 4 in the appendices indicate that, in the long term, the intensity of conflicts (IC) and the duration of conflicts (DC) are the primary variables driving ecological

damage (Drachuk et al., 2023). Specifically, the coefficients for IC are statistically significant and positively correlated with deforestation, biodiversity loss, and pollution. This suggests that these forms of environmental degradation worsen as conflict intensity increases. However, the impact of IC on land degradation is less significant, which may be due to the complex interplay between conflict-related activities and land use changes (Lawrence et al., 2015). For instance, in the case of the Syrian Civil War, the intense and prolonged conflict led to widespread deforestation as forests were cleared for fuel and agricultural expansion by displaced populations. Similarly, the Democratic Republic of Congo has seen significant biodiversity loss due to intense conflict in regions rich in natural resources, where armed groups have exploited wildlife and natural habitats to fund their activities. The duration of conflicts (DC) also plays a crucial role in ecological damage, with more pronounced effects on deforestation, biodiversity loss, and land degradation. Prolonged conflicts, such as the decades-long conflict in Afghanistan, have led to the degradation of arable land due to the abandonment of agricultural practices and the destruction of irrigation systems, exacerbating environmental damage over time.

Regarding the third conflict factor, displacement and refugee numbers, the findings indicate a minor or negligible impact on environmental degradation variables. This could be attributed to the fact that while displaced populations may contribute to localized environmental stress, such as deforestation for temporary shelters or overuse of limited resources, their impact is relatively small compared to the broader, more systemic effects of conflict intensity and duration (Van der Vet, 2024). For example, while refugee camps in places like Sudan have caused localized environmental issues, these effects are overshadowed by the broader ecological damage driven by the ongoing conflict in the region.

Turning to the economic control variables, the long-term analysis reveals no significant evidence that economic growth (GDP) and inflation (CPI) adversely affect environmental degradation. The coefficients for these variables are statistically insignificant, suggesting that economic conditions, as measured by GDP and CPI, do not directly contribute to environmental destruction in the context of this study.

These findings challenge the often-assumed link between economic growth and ecological damage, particularly the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially increases with economic growth but eventually decreases as societies become wealthier and more capable of investing in environmental protection (Certini et al., 2013). In this case, the lack of a significant relationship may indicate that other factors, such as technological advancements or environmental regulations, could mitigate economic growth's potential negative environmental impact.

Inflation's insignificance in the model further underscores that short-term economic fluctuations, such as changes in price levels, do not have a direct and measurable impact on long-term environmental outcomes (Elasha, 2014).

However, the analysis does reveal a small but significant coefficient for the poverty rate, indicating its slight implication in ecological damage. This finding is consistent with the notion that poverty can lead to environmental harm through mechanisms such as overexploitation of natural resources, unsustainable agricultural practices, and the inability to invest in environmentally friendly technologies (Sylvester, 2012). For example, in many developing regions, impoverished communities rely heavily on deforestation for fuel and agriculture, contributing to environmental deterioration. The situation in sub-Saharan Africa, where poverty and environmental degradation are often intertwined, illustrates how poverty can drive harmful environmental practices.

The results related to the PECE coefficients further solidify the significant role that war and conflict factors play in driving deforestation, biodiversity loss, pollution levels, and land degradation. The PECE aggregate index, which represents the environmental conditions prior to the onset of conflicts, has statistically insignificant coefficients. This indicates that the recent environmental deterioration observed in the study is not merely a continuation of pre-existing environmental trends but is instead driven by new factors, most notably war and conflict (Drožđek et al., 2020).

This finding is significant as it underscores armed conflicts' disruptive and transformative impact on the environment. In regions where conflicts have erupted, the environmental damage is not simply an exacerbation of ongoing degradation but is instead a direct consequence of the conflict itself. For example, in the Amazon rainforest, deforestation rates surged during the Colombian conflict, driven by the clearing of land for illicit crop cultivation and the displacement of rural populations (Karaca, 2018). This degradation was not a mere continuation of previous trends but was directly linked to the dynamics of the conflict.

Similarly, in the case of biodiversity loss, conflicts often destabilize protected areas, such as poaching and illegal logging, as seen in the Virunga National Park during the conflict in the Democratic Republic of Congo. The statistically insignificant PECE index suggests that the environmental degradation in such cases is not simply a worsening of existing conditions but rather a result of the new pressures introduced by the conflict (Leaning, 2002).

The lack of significance in the PECE coefficients also implies that pre-conflict environmental policies or conditions may have been ineffective in preventing or mitigating the environmental impacts of subsequent conflicts. This highlights the need for more robust environmental safeguards and conflict-sensitive ecological management strategies, especially in unstable regions.

The short-term results are generally consistent with the long-term coefficients, yet they reveal that the impact of war and conflict factors on environmental deterioration is less pronounced in the short term compared to the long term (Meaza et al., 2024). This difference suggests that the ecological consequences of conflicts may accumulate over time, with the immediate effects being less severe but growing more significant as the conflict persists.

In the short term, the disruption caused by conflict may lead to localized environmental damage, such as deforestation for immediate resource needs or pollution from military activities. However, these impacts might be initially limited in scope due to the transient nature of early conflict stages or the focus on immediate survival and military objectives rather than extensive environmental exploitation.

As conflicts drag on, however, the cumulative effects become more evident. The prolonged disruption of governance, the collapse of environmental regulations, and the sustained exploitation of natural resources can lead to more widespread and severe ecosystem degradation (Lawrence et al., 2024). For example, in the early years of the Yugoslav Wars, ecological damage was relatively contained, but as the conflicts continued, the destruction of industrial facilities and infrastructure resulted in significant pollution and long-term ecological harm.

This finding also aligns with the concept of environmental resilience, where ecosystems may initially absorb shocks but gradually degrade under prolonged pressure. In regions like Darfur, short-term environmental impacts from the conflict were initially localized, but as the conflict

persisted, widespread desertification and land degradation occurred due to the displacement of populations and overuse of natural resources (McSorley, 2013). .

In summary, while the short-term impacts of war and conflict on the environment are evident, they are less severe than long-term effects. This emphasizes the importance of addressing environmental concerns early in conflict situations, as prolonged conflict can lead to escalating and potentially irreversible environmental damage.

5. Policy Implications

Several key policies must be prioritized to combat ecosystem degradation caused by wars and conflicts, especially considering the violations of international humanitarian law (IHL). Firstly, stricter enforcement of IHL provisions related to protecting the environment during armed conflicts is essential (Jayasinghe, 2024). These laws prohibit targeting natural resources and ecosystems, and their enforcement could mitigate deforestation, biodiversity loss, and pollution, exacerbated by intense and prolonged conflicts (Limaj et al., 2024).

International bodies and governments must also work together to implement conflict-sensitive environmental management strategies. These strategies should include monitoring and safeguarding ecologically significant areas, particularly in conflict-prone regions (Schon, 2020). For instance, enhancing protection measures for forests, wildlife reserves, and water sources could prevent the exploitation of these resources by armed groups, which has been a significant driver of environmental degradation in conflict zones like the Democratic Republic of Congo and the Amazon rainforest.

Moreover, establishing rapid response mechanisms to address environmental damage during conflicts is crucial. These mechanisms should focus on mitigating the immediate impacts of military activities, such as pollution from the destruction of infrastructure and the unsustainable extraction of natural resources (Wenning and Tomasi, 2023). By addressing these issues early, the accumulation of long-term environmental damage can be minimized.

Finally, post-conflict environmental restoration programs should be integrated into peacebuilding efforts. These programs must prioritize the rehabilitation of damaged ecosystems, reforestation, and rebuilding sustainable agricultural practices to ensure long-term environmental recovery (Karaca, 2018). For example, in post-conflict regions like Afghanistan, efforts to restore irrigation systems and reclaim arable land could reverse some ecosystem degradation caused by prolonged warfare.

By implementing these policies and upholding the principles of international humanitarian law, it is possible to reduce the environmental toll of wars and conflicts, ensuring that the natural world is better protected even in human strife.

6. Conclusion

this study highlights the profound and lasting impact of armed conflicts on the environment, with the intensity and duration of conflicts emerging as key drivers of environmental degradation. The findings underscore the necessity of strictly enforcing international humanitarian law to protect the environment during times of war. Violations of international humanitarian law, such as the targeting of natural resources and ecosystems, have led to significant deforestation, biodiversity loss, and pollution in conflict zones around the world. These destructive activities violate legal norms and have severe and long-lasting ecological consequences.

The study also reveals that the environmental degradation associated with conflicts is not merely a continuation of pre-existing trends but is driven by the conflicts. This emphasizes the need for more robust and proactive environmental safeguards, particularly in unstable regions. Conflict-sensitive ecological management strategies should be integrated into military planning and post-conflict reconstruction efforts to mitigate and reverse environmental damage.

Future research should focus on exploring the effectiveness of existing international humanitarian law provisions in protecting the environment during conflicts and identifying gaps in their enforcement. Additionally, there is a need for further studies to examine the role of international and local environmental organizations in conflict zones and how they can better collaborate with governments and military forces to safeguard ecological resources. Investigating the potential for incorporating environmental protection into peacebuilding initiatives and the long-term ecological restoration of conflict-affected areas also presents an open research window for future studies. By continuing to explore these areas, we can develop more comprehensive strategies to prevent and mitigate the environmental impacts of armed conflicts.

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Declarations:

Data availability statement: The raw/processed data required to reproduce the above findings cannot be shared at this time due to legal/ ethical reasons.

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Appendices

Table 2. Variables Overview

Variable	Notation	Definition	Sources
Dependent variables			
Deforestation	DEF	Deforestation Rate: the rate at which forest area is lost annually, typically expressed in hectares per year.	Food and Agriculture Organization of the United Nations
Biodiversity loss	BIO	Species Richness: measures the number of species in a specific area. A decline in species richness over time indicates biodiversity loss.	Global Biodiversity Information Facility (GBIF)
Pollution	POLL	Environmental Performance Index: a comprehensive index that ranks countries based on their environmental health and ecosystem vitality.	The official EPI website (epi.yale.edu)
Land degradation	LAND	Normalized Difference Vegetation Index: an indicator that measures vegetation health and density	NASA Earth Observing System Data and Information System (EOSDIS)
Conflict-related factors			
Intensity of conflict	IC	Intensity of conflict, measured by battle-related deaths	the Uppsala Conflict Data Program (UCDP)
Duration of conflict	DC	It gives the start and end dates of conflicts, allowing to calculate the duration of each conflict	the Uppsala Conflict Data Program
Displacement and refugee numbers	DRN	representing the number of people displaced internally or seeking refuge in other countries due to conflict	United Nations High Commissioner for Refugees (UNHCR)
Control variables			
Inflation rate	CPI	variation in consumer price index	WDI database of the World Bank (WDI)
Real GDP growth	GDP	growth rate of the real gross domestic product	WDI
Poverty rate	POV	percentage of a population living below the poverty line, which is the minimum income level deemed necessary to meet basic needs	WDI
pre-conflict ecological conditions	PECE	Aggregate index on various environmental indicators, including air and water quality, which helps establish the environmental baseline before conflicts	UN- the Global Environmental Monitoring System (GEMS)

Table 3. Descriptive statistics

Variable	Min	Max	Mean	Std. Dev.
DEF	0.2037	38.6294	0.9627	1.896
BIO	0.0367	2.8627	0.5348	0.9372
POLL	0.0927	7.0254	0.3651	1.8627
LAND	0.2549	0.8671	0.6521	0.2348
IC	84.9367	111.9956	0.0962	0.6330
DC	38.318	54.0414	-0.0001	0.1653
DRN	1280	665.000	55.038	13.542
CPI	1.316	58.327	3.4581	2.2592
GDP	-2.135	7.1152	5.0135	2.3768
POV	5.8126	72.3695	21.9327	15.8627
PECE	1.4297	9.3672	3.1257	1.0937

Source: Calculations by the authors.

Table 4. Environmental degradation

	(1)	(2)	(3)	(4)
Long-term coefficients				
Conflict-related factors				
IC	0.129**	0.156**	0.131***	0.092*
	(0.064)	(0.078)	(0.032)	(0.046)
DC	0.138**	0.104**	0.085*	0.127**
	(0.069)	(0.052)	(0.043)	(0.063)
DRN	0.004*	0.003	0.002*	0.057
	(0.002)	(0.026)	(0.001)	(0.178)
Control variables				
CPI	0.021*	0.526	0.129	0.006*
	(0.001)	(0.028)	(0.064)	(0.003)
GDP	0.008*	0.007*	0.038*	0.011*
	(0.004)	(0.003)	(0.019)	(0.005)
POV	0.011*	0.021*	0.014*	0.008*
	(0.005)	(0.010)	(0.007)	(0.004)
PECE	0.253	0.071	0.098	0.076
	(0.327)	(0.517)	(0.114)	(0.307)
Short-term coefficients				
Conflict-related factors				
ΔIC	0.051**	0.063**	0.073***	0.032*
	(0.025)	(0.031)	(0.022)	(0.016)
ΔDC	0.043**	0.064**	0.041*	0.081**
	(0.021)	(0.032)	(0.020)	(0.040)
ΔDRN	0.003*	0.005	0.002*	0.034
	(0.002)	(0.084)	(0.001)	(0.230)
Control variables				
ΔCPI	0.010*	0.106	0.357	0.003*
	(0.005)	(0.238)	(0.802)	(0.001)
ΔGDP	0.004*	0.005*	0.012*	0.008*
	(0.002)	(0.002)	(0.006)	(0.004)
ΔPOV	0.007*	0.012*	0.008*	0.003*

	(0.003)	(0.006)	(0.004)	(0.001)
ΔPECE	0.101	0.154	0.118	0.236
	(0.087)	(0.247)	(0.354)	(0.417)
skewness/kurtosis	3.66	5.12	3.02	6.93
(Prob>chi2)	(0.2677)	(0.3525)	(0.1877)	(0.1672)
Wald/LL	-136.27	-148.13	-101.56	-99.85
(Pvalue)	(0.000)	(0.000)	(0.000)	(0.000)
test of Hansen	0.42	0.72	0.54	0.39
	(0.000)	(0.000)	(0.000)	(0.000)
AR(1)	(0.000)	(0.000)	(0.000)	(0.000)
AR(2)	(0.892)	(0.528)	(0.892)	(0.645)
test of REST	0.3471	0.2698	0.3471	0.1824

Note: This Table displays the regression results for Eq. (1). Column (1) reports the regression with deforestation as the dependent variable, Column (2) focuses on biodiversity loss, Column (3) on pollution, and Column (4) on land degradation. The results are divided into two sections: short-term and long-term analysis. In each section, the regressors consist of conflict-related factors and control variables. All regression estimates are obtained using the difference Generalized Method of Moments (GMM), with robust T-values in parentheses.