



Armed conflict-driven environmental degradation and uneven socio-ecological resilience in Tigray, Ethiopia

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ABSTRACT

The armed conflict on Tigray, in Ethiopia (2020–2022), triggered one of the most alarming socio-ecological crises in recent history, jeopardizing decades of progress in environmental restoration and livelihood development. Widespread deforestation, soil degradation, and the collapse of local institutions have left the region's ecosystems and communities in a state of acute vulnerability. Using an integrated socio-ecological systems (SES) framework, the study applied vegetation index (NDVI) analysis, soil erosion modeling (RUSLE), vegetation plot surveys, and household-level socio-economic assessments across three districts. This study underscores the urgency of coordinated recovery by revealing how the armed conflict has accelerated vegetation loss, by 57% in Abergelle-Yechila, 55.5% in Samre, and 10.9% in Atsbi, and increased annual soil erosion by up to 5.5 tons/ha. Livelihoods were shattered due to infrastructure destruction, livestock loss, blocked markets, and restricted mobility. Fuelwood dependence soared in the absence of electricity and functional governance, deepening forest degradation. Yet, in contrast, Atsbi's stronger enforcement of local bylaws offered a glimpse of resilience, demonstrating how community-based conservation can mitigate environmental collapse even amid conflict. These findings highlight the urgent need for conflict-sensitive restoration strategies, including reforestation, sustainable land management, and the revitalization of local governance. Prioritizing alternative energy sources and fostering active community engagement are essential steps toward rebuilding a more resilient socio-ecological system in post-conflict Tigray.

1. Introduction

Armed conflicts have profound and multifaceted impacts on natural resources, ecosystems, and livelihoods, with consequences that extend far beyond immediate humanitarian crises. Environmental degradation, including deforestation, biodiversity loss, soil erosion, and water contamination, is a well-documented outcome of violent conflicts [1–3].

For instance, between 1946 and 2010, conflict emerged as a leading predictor of wildlife population declines, exemplified by the catastrophic loss of biodiversity in Mozambique's Gorongosa National Park during its civil war [1]. Similarly, prolonged conflicts in Colombia and the Democratic Republic of Congo have driven extensive deforestation, habitat destruction, and ecosystem degradation, displacing communities and undermining conservation efforts [4–6]. Military activities further

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exacerbate environmental damage, as seen in Iraq, where water resources were contaminated by explosives [7], and in Ukraine, where attacks on infrastructure disrupted water access and food security [8].

The degradation of land and agricultural systems further intensifies food insecurity and disrupts livelihoods. Soil erosion, salinization, and the loss of arable land documented in conflict-affected regions such as Tigray, Ethiopia, and Sudan severely reduced agricultural productivity [9–14]. These environmental impacts are compounded by direct attacks on farming assets, as seen in Tigray, where oxen were looted and croplands destroyed, crippling local food production [15]. Conflicts also force shifts in resource use, with communities increasingly relying on unsustainable practices such as illegal logging, artisanal mining, or groundwater overexploitation, as observed in Syria, Afghanistan, and Colombia [16–18]. Such coping strategies accelerate environmental destruction while deepening socio-economic vulnerabilities, particularly for marginalized groups, including women, youth, and displaced populations [19–21].

The Tigray region of Ethiopia has long been one of the most conflict-affected areas in the Horn of Africa, experiencing three major armed conflicts over the past five decades. These repeated conflicts have profoundly impacted the region's social, economic, environmental, and institutional systems [20,22,23]. Since the 1980s, the Tigray government and local communities have undertaken extensive environmental restoration efforts in collaboration with the federal government and NGOs [24,25]. Notably, woody vegetation cover increased from less than 3% in the late 1980s to 17% by 2020, contributing to a 4.16% rise in smallholder farmers' income [24,26]. These efforts earned Tigray the 2017 Future Policy Gold Award from the World Future Council and UNCCD [24]. Between 1991 and 2020, significant progress was made through soil and water conservation, sustainable land management, and afforestation programs [10,27]. However, the armed conflict that began in November 2020 reversed decades of restoration, triggering a severe humanitarian and environmental crisis. The conflict has led to widespread environmental degradation, deforestation, agricultural damage, and emissions, driven by military destruction, overuse of resources, and the collapse of governance and public services [10,26,28]. As electricity and fuel supplies were disrupted, communities relied heavily on firewood, intensifying deforestation and soil erosion [26]. These impacts are far-reaching and long-lasting, threatening local livelihoods, ecosystems, and national sustainability goals. Urgent restoration and conflict-sensitive environmental recovery are critical for sustainable development in post-conflict Tigray.

Environmental degradation threatens lives and livelihoods, especially during and after armed conflicts [3]. Sustainable livelihoods depend on the protection and restoration of the environment. To expedite recovery, assessing the impacts of armed conflicts, prioritizing affected areas, and implementing rehabilitation measures are essential. Effective restoration can revive livelihoods that depend on natural resources and enhance resilience in the post-conflict period. Indirect impacts include the footprint of displaced populations, the collapse of environmental governance, data gaps, and inadequate funding for environmental protection, among others [3].

Post-conflict reconstruction efforts often prioritize humanitarian relief, security, and political reconciliation, yet addressing environmental damage is equally critical, as it directly impacts health and livelihoods during recovery [3]. Despite its urgency, the impact of the Tigray armed conflict on natural resources and socio-economic systems remains largely understudied, with existing research limited primarily to remote sensing analyses. While broader environmental impacts of armed conflict are well-documented, localized consequences using particularly the interplay between conflict, environment, and livelihoods, demand deeper investigation, as seen in Tigray's overlooked case. This study aims to bridge this gap by assessing the armed conflict's impact on natural resources, livelihoods, and offering context-specific restoration recommendations.

The objectives of the study were: i) to investigate the impacts of the

armed conflict on natural resources and assess its effects on local environmental restoration and conservation practices, including the capacity to implement these practices effectively, ii) to analyze the socio-economic consequences of the armed conflict, including displacement, access to resources, and livelihoods, iii) to evaluate both formal and community-driven recovery efforts and their effectiveness in restoring and conserving natural resources, and iv) to propose targeted and actionable recommendations for relevant stakeholders to enhance sustainable recovery and restoration efforts.

In this study, we adopted a socio-ecological systems (SES) framework to conduct a comprehensive and integrated analysis of the impacts of armed conflict on natural resources. The SES approach provides a robust theoretical foundation for understanding the complex and dynamic interplay between human societies and natural ecosystems, particularly in conflict-affected regions [29]. Rooted in resilience theory, institutional analysis, and complex adaptive systems thinking, the SES framework conceptualizes social and ecological components as deeply interconnected and co-evolving [30]. Several strengths make this approach particularly well-suited for studies of post-conflict environments. First, it offers a holistic perspective that integrates ecological, economic, political, and cultural dimensions, moving beyond narrow, sectoral analyses to capture the full complexity of recovery challenges [31]. Second, by incorporating institutional and governance analysis, the SES framework helps reveal how conflict undermines collective resource management and adaptive capacity [32]. Finally, its emphasis on resilience enables the identification of pathways through which systems can absorb shocks and reorganize to sustain critical functions [33]. In the case of Tigray, applying the SES framework allowed us to explicitly link ecological degradation, such as deforestation, soil erosion, and biodiversity loss, to governance weaknesses and livelihood vulnerabilities, while situating these linkages within the region's unique socio-ecological context, including its enclosure programs and community-based natural resource management systems. This integrative perspective is crucial for informing sustainable recovery strategies in conflict-affected landscapes.

2. Methods

2.1. Study area

The study focused on three purposefully selected districts (woredas) in the Tigray region in Ethiopia: Abergelle-Yechila, Samre, and Atsbi (Fig. 1). These districts were chosen to represent varying levels of armed conflict intensity (high, medium, and low), and different agro-ecological zones (highland, midland, and lowland). The classification of armed conflict severity was based on the framework developed by Weldegebriel et al. [21]. These districts served as case studies to illustrate the impact of the armed conflict on the Tigray region's natural resources and prior conservation efforts. The Atsbi watershed spans 28,054 hectares, Samre covers 59,344 hectares, and Abergelle-Yechila encompasses 55,347 hectares.

In the study areas, cropping and livestock husbandry have long served as the primary sources of livelihood for local communities. Atsbi district is agro-ecologically situated in the highland escarpment of eastern Tigray, while Samre lies in the south-eastern midland agro-ecological zone. The populations of both Atsbi and Samre predominantly practice a mixed crop-livestock farming system, cultivating staple crops such as barley, wheat, teff, beans, and various vegetables. This is supplemented by livestock rearing, petty trade, and remittances from relatives living in urban centers and abroad. In contrast, agro-pastoralism remains the predominant livelihood strategy in Abergelle-Yechila, where rural households rely heavily on both crop cultivation and livestock raising, including seasonal grazing movements to sustain their herds. In these study areas, most of the population speaks Tigrigna and maintains strong social networks traditionally rooted in religious institutions and beliefs. Before the armed conflict, local government

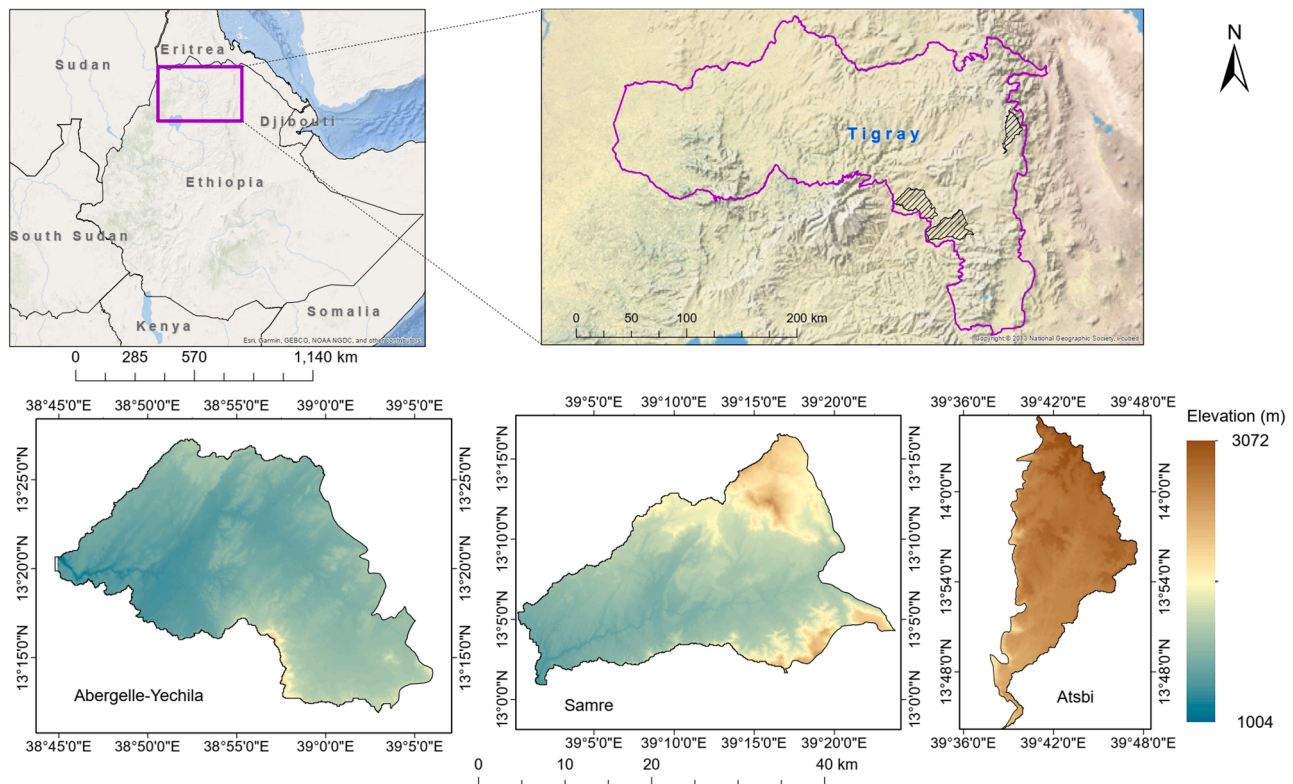


Fig. 1. Map of the study areas showing agro-ecological zones classified by elevation gradients. The three study watersheds (Abergelle-Yechila, Samre, and Atsbi) are marked by black stripes within the Tigray regional boundary (top-right panel).

offices and agricultural extension agents played vital roles in delivering services; however, these institutions have largely ceased to function due to the armed conflict. As a result, churches and certain humanitarian organizations have become the primary active stakeholders supporting communities throughout the crisis in Tigray.

These districts provided representative samples, showcasing the extensive effects of the armed conflict on natural resources, socio-economic landscapes, and restoration efforts. Specific sites within each district were carefully selected to capture the diverse impacts of the armed conflict on ecological restoration efforts. Using the watershed approach, two watersheds were purposively selected in each district. Within each watershed, we identified specific enclosures and conservation sites and established control sample plots for comparative analysis. The selection of conservation areas considered their strategic battlefield positioning and prior restoration efforts, which offered a baseline for assessing ecological health before the armed conflict.

2.2. Data collection

The study utilized a mixed-methods approach, employing both primary and secondary data sources, to comprehensively investigate the armed conflict's impact on natural resources and socio-economic landscapes in the selected districts within Tigray. Primary data collection included field surveys, observations, Key Informant Interviews (KIIs), and Focus Group Discussions (FGDs). The primary data were complemented with secondary data from satellite imagery, reports, articles, and media.

The research framework for this study is grounded in a human-environment systems approach, linking conflict intensity to ecological degradation and socio-economic disruption across three distinct districts in the Tigray region. These districts were purposefully selected to represent a range of conflict severities and agroecological zones, enabling a comparative analysis of conflict-induced impacts (see Fig. B1 in the appendix). The framework integrates bio-physical and socio-

economic data through a mixed-methods design, combining satellite imagery, household surveys, focus group discussions, and key informant interviews. Using a watershed-based sampling strategy, the study assessed changes in vegetation, land use, soil erosion, and livelihoods before and after the conflict. Analytical tools, including the Normalized Difference Vegetation Index (NDVI), Revised Universal Soil Loss Equation (RUSLE) modeling, and both descriptive and inferential statistics, were employed to measure environmental damage and community resilience. The framework also captures local recovery mechanisms and restoration practices, offering a comprehensive lens to understand the intertwined effects of the armed conflict on natural resources, institutions, and livelihoods in a fragile, post-conflict landscape.

2.2.1. Socio-economic data

This study employed a multistage sampling technique to collect the necessary data. In the first stage, districts characterized by diverse natural resources, including agricultural land, forests, water, soil, and other biodiversity components, which had been severely affected by prolonged armed conflict, were purposively selected based on predefined criteria. These criteria included (i) the extent of damage to natural resources, (ii) the accessibility and safety of the study sites, and (iii) the presence of internally displaced people (IDP) centers, as displaced populations often depend heavily on natural resources for their livelihoods. In the second stage, priority was given to districts (locally known as *woredas*) that had experienced prolonged exposure to both climate-induced stressors and armed conflict over natural resources. In the third stage, districts that had shown notable environmental restoration efforts before the onset of the armed conflict were also considered. Based on these criteria, Abergelle-Yechila, Samre, and Atsbi were chosen as case study areas.

Using Cochran's formula [34], 305 sample households were randomly selected through a probability proportional to size (PPS) sampling method, based on the population size of each district.

$$n = \frac{(Z_{\alpha/2})^2 p(1-p)}{(e)^2} \quad (1)$$

Where n denotes a required sample size, Z shows the desired confidence level, p represents the proportion, and e denotes the level of precision or acceptable error.

The study participants were first asked for their informed consent before they participated in this study (see Appendix A for the consent form used in this study). All participants gave their informed consent for inclusion before they participated in the study. Primary data were collected through household surveys using a semi-structured questionnaire designed in KoboToolbox, a versatile platform suitable for offline data collection with Android devices. The survey was conducted between 18 June and 12 July 2024 and covered natural resource management, conflict-induced impacts, restoration patterns, recovery challenges, and resilience strategy topics.

Qualitative data were gathered through FGDs and KIIs. FGDs included 24 participants (eight from each district), selected based on age, gender, location, and wealth status to ensure diverse perspectives. These participants represented various community segments, including women, youth, and adult men. Discussions were recorded and transcribed for triangulation and in-depth analysis. For KIIs, 18 participants (six from each district), including knowledgeable residents, experts, and community leaders, were interviewed for their insights into local vegetation resources and recovery mechanisms. Both FGDs and KIIs provided detailed qualitative insights into the impacts of the armed conflict on natural resources and the diverse strategies implemented for recovery. This combination of data collection methods ensured a comprehensive understanding of the study's objectives.

2.2.2. Bio-physical data

To assess land use and land cover in the watersheds, we utilized Sentinel 2 Level-2A satellite products with a spatial resolution of 10 m for the required bands. Additionally, Digital Elevation Model (DEM) data from the Shuttle Radar Topographic Mission (SRTM) were acquired from the USGS website (<https://earthexplorer.usgs.gov/>). In addition to the satellite imagery, ground truth datasets, photographs of observed damages on soil and water conservation structures, and their coordinates were collected.

Our site selection process employed a stratified systematic approach to ensure representative sampling of vegetation conditions across conflict-affected areas. Following preliminary assessments in the three districts, we identified paired enclosure sites in each location, strategically selecting one severely damaged and one moderately impacted enclosure per district to capture the spectrum of conflict-related degradation. For vegetation data collection, we implemented a systematic transect-based survey methodology. Transect lines were precisely oriented and evenly spaced within each enclosure to maximize spatial coverage while maintaining methodological consistency across sites. This rigorous sampling framework ensured comprehensive characterization of vegetation structure and composition while controlling for potential spatial biases in disturbance patterns. Accordingly, three parallel transect lines, spaced 1 km apart, were set up across the enclosures to sample the vegetation. Along each transect, three randomly selected sample plots measured 20 m x 20 m were established, totaling 18 sample plots per study site. These main plots were placed at 100 m intervals along the transects to ensure thorough coverage of the study area. In addition, control sample plots were established for comparative analysis. In each sample plot, live, damaged, and dead trees were recorded, noting their species and condition. Damage levels were categorized following the approach of Da-zhi et al. [35] as: (i) No damage (<5% of the vegetation is damaged), (ii) slightly damaged (10–25% of the vegetation is damaged), (iii) partially damaged (25–65% of the

vegetation is damaged), and (iv) fully damaged ($\geq 65\%$ of the vegetation is damaged). GPS coordinates and measurements of deadwood size, length, and condition were recorded. Information from local leaders and farmers helped identify the species most affected. Data on soil and water conservation were gathered through satellite imagery and ground truth observations.

2.3. Data analysis

2.3.1. Socio-economic data analysis

The quantitative data collected using Kobo Toolbox software were cleaned, coded, and analyzed using STATA version 17. Descriptive statistical techniques, such as mean, standard deviation, percentage, and frequency distributions, were applied to identify patterns and trends within the dataset, offering valuable insights into the study. To assess the environmental and livelihood impacts of the armed conflict, inferential statistics, including the t -test, were used to analyze mean differences in environmental damage. This analysis enabled us to conclude the effects of the armed conflict on the environment and the livelihoods of affected communities. The statistical analysis provided a solid quantitative framework for understanding the extent and severity of environmental damage caused by the armed conflict, offering critical insights into its impact on ecosystems and local communities.

A phenomenological qualitative approach was also used to explore households' lived experiences regarding the armed conflict's effects on the environment and livelihoods. This approach played a crucial role in understanding the sustainable recovery strategies adopted by local households. Additionally, content analysis was employed to examine the specific strategies reported by households and assess the effectiveness of the recovery mechanisms they implemented. The combination of phenomenological and content analysis methods offered a comprehensive understanding of the best practices and lessons learned in achieving sustainable post-conflict recovery. Employing a mixed-methods approach, the study applied triangulation to analyze, validate, and substantiate its findings. By comparing results from both qualitative and quantitative data sources, triangulation enhanced the credibility and consistency of the conclusions, thereby strengthening the overall reliability of the study.

2.3.2. Vegetation data analysis

The Sentinel-2 imagery used in this study was sourced from the Copernicus program through Google Earth Engine (GEE). The data comes pre-processed with several key corrections. It is geometrically corrected via orthorectification and accurately geo-referenced to the WGS84 geographic coordinate system. Radiometric calibration is performed at Level-1C (Top of Atmosphere), and atmospheric correction to Level-2A (Bottom of Atmosphere) is applied using the Sen2Cor processor. These preprocessing steps ensure the data is ready for biophysical analysis without requiring further geometric, radiometric, or projection corrections. Hence, the corrected Sentinel-2 Level-2A satellite image was used to classify land use and vegetation cover in the Atsbi, Abergelle-Yechila, and Samre watersheds using the GEE platform. A supervised classification approach and accuracy assessment using 250 GPS points for ground truthing were conducted to validate the results. The Normalized Difference Vegetation Index (NDVI) was applied to assess vegetation changes. NDVI-based threshold (> 0.3) analyzed vegetation changes pre- and post-conflict. ArcMap 10.8 was used to map the spatial distribution of conflict impacts on natural resources.

Descriptive statistics were used to estimate the number of woody species lost per hectare across various sites and to assess damage to nursery resources. Regression analysis was used to examine the relationship between distance from urban areas and the volume of harvested wood, illustrating how proximity to towns influences resource

extraction, particularly during periods of armed conflict. Furthermore, independent *t*-tests and one-way ANOVA were applied to compare the mean volume of harvested wood per plot and the percentage of vegetation cover across sites.

2.3.3. Soil and water conservation data analysis

The Revised Universal Soil Loss Equation (RUSLE) was applied to estimate soil erosion, considering factors like rainfall, slope, and land cover changes over time. The RUSLE was employed to quantify soil loss in the selected watersheds. The equation used for soil loss computation is given as:

$$A = R * K * L * S * C * P \tag{2}$$

Where **A** is the computed soil loss per unit area (ton. ha⁻¹. y⁻¹); **R** is rainfall and runoff erosivity factor (MJ.mm. ha⁻¹. h⁻¹. y⁻¹); **K** is soil erodibility factor (ton.h.MJ⁻¹.mm⁻¹); **L** is slope-length factor (dimensionless); **S** is slope-steepness factor (dimensionless); **C** is cover-management factor (dimensionless); and **P** is conservation supporting practices factor (dimensionless).

Rainfall and land use/land cover across different years were identified as key factors influenced by the armed conflict. Therefore, we developed land use/land cover maps for both the pre-conflict year (2020) and the post-conflict year (2024). We used the mean annual rainfall data from the Atsbi, Wukro, Samre, and Yechila stations and applied spatial interpolation to determine the R factor. Soil erodibility (K) was assessed following the guidelines provided by Stone and Hilborn [36].

The R factor was calculated using the relationship tested and adapted for the highlands of northern Ethiopia by Hurni [37] through the following equation:

$$R = -8.12 + 0.562RF \tag{3}$$

Where **RF** represents the mean annual rainfall (mm) and **R** is the erosivity factor

The slope and flow accumulation were derived from the digital elevation model to compute the topographic factor (LS). The slope length (L) and slope steepness (S) were determined using the equation developed by Wischmeier and Smith [38]:

$$LS = (Flow\ accumulation * cellvalue / 22.1)^m * (0.065 + 0.045 * S + 0.0065 * S^2) \tag{4}$$

The Soil Erodibility Factor (K) was estimated using soil texture and organic matter content [36]. The C and P factors were generated for various land use types and soil and water conservation structures, drawing on information gathered from multiple literature sources applicable to the Ethiopian landscape [37,39]. In this study, the main input factors of the RUSLE model were calibrated to enhance its suitability for the local environment. The Rainfall Erosivity Factor (R) was adjusted using annual rainfall data from the Atsbi, Abergelle-Yechila, and Samre meteorological stations. To fill data gaps, rainfall estimates from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) at 5 km resolution were incorporated as a supplementary source. The K factor was calibrated based on field surveys and direct observations, with special focus on soil texture and organic matter content. The Slope Length and Steepness Factor (LS) was derived from a 30-meter resolution Digital Elevation Model (DEM), with calibration involving adjustments to slope length values to better reflect actual topographic conditions. The Cover Management Factor (C), recognized as one of the most variable and subjective inputs, was calibrated through land cover classification supported by field surveys, as detailed in Table 1. Similarly, the Support Practice Factor (P) was calibrated by assessing the types, extent, and effectiveness of soil and water conservation measures implemented at the study sites, following the approach outlined in [39] (Table 1). Model validation was performed by comparing our results with those of previous studies conducted in

Table 1
Crop management (C) and Conservation practice (P) factors and associated soil and water conservation (SWC) structures by land use/land cover type.

Land use/Land cover	C-Factor	Soil and water conservation (SWC) structures	P-Factor
Cultivated land (CL)	0.12	Contouring, Stone bund, Stone bund with trenches, and Stone bund grassed on cropland	0.39
Shrub land (SL)	0.02	Stone bund, Trench, Stone bund with trenches on rangeland	0.23
Water body (WB)	0.00	-	-
Built-up (BU)	0.00	-	-
Irrigated land (IRR)	0.12	Contouring, Stone bund, Stone bund with trenches, and Stone bund grassed on cropland	0.39
Bare land (BA)	0.12	Contouring, Stone bund, Stone bund with trenches, and Stone bund grassed on cropland	0.39
Forest land (FR)	0.01	Contour stone bunds/lines-narrow spacing (10–15 m)	0.5

Ethiopia and other regions exhibiting similar environmental and landscape characteristics [39,40].

3. Results and discussion

3.1. Impact of armed conflict on the socio-economic landscape

3.1.1. Socio-demographic characteristics

The socio-demographic characteristics of the sample households indicated that 67.5% were male-headed, while 32.5% were female-headed. Notably, in Samre, 42.6% of the households were female-headed (see Table B1 in the appendix). In Samre, 64.4% of farm households had land holdings of less than 0.25 hectares, compared to 66.9% in Abergelle-Yechila, indicating better access to land in Abergelle-Yechila. Many landless men from Samre migrated in search of work, and the armed conflict contributed to increased rates of divorce and widowhood. Approximately 11.5% of household heads were aged 15–29, 78.7% were between 30 and 64, and 9.8% were over 64. Regarding education, 33.8% had no formal education, 49.8% had completed primary education, 13.2% had finished secondary school, and 2.6% had attained college education. The average household size was 5.5 members, slightly smaller than the national average of 5.76 in 2019 [41].

Table 2
Impacts of armed conflict on socio-economic landscapes in selected districts in Tigray.

Category	Impact	Count	Percent
Social impacts	School interruption	214	70.2
	Displacement	153	50.2
	Loss of jobs	123	40.3
	Physical disability	39	12.9
	Death	54	17.7
	Rape	21	6.9
Agricultural services	Reduced working hours	284	93.4
	Lack of marketing	226	74.1
	Agricultural inputs not available	287	94.4
	Limited or no access to agricultural finance	290	95.1
Agricultural impacts	Movement restrictions	288	94.7
	Irrigation damage	173	61.8
	Loss of livestock	198	65
Income impacts	Damage to farm tools	135	44.3
	Income reduction	241	78.9

3.1.2. Socio-economic consequences

Results of the selected case studies in Tigray suggest that the two years of armed conflict have drastically affected the socio-economic landscape of the population in various ways (Table 2). These include social, agricultural, physical and livelihood-related impacts. According to the respondents' accounts, the armed conflict has led to several social crises, including school interruption (70.2%), displacement (50.2%), unemployment (40.3%), physical disability (12.8%), death (17.7%), and incidents of rape (6.9%).

Parents were unable to send their children to school due to the outbreak of the armed conflict. This was largely attributed to the devastation of educational infrastructure, with school facilities and materials being either looted or demolished. The frequent armed conflicts across Tigray made it challenging to conduct teaching and learning activities. Parents were hesitant to send their children to school due to safety concerns. Key informants reported that many schools that were not severely damaged by artillery shelling were repurposed as shelters for thousands of internally displaced people (IDPs). As a result, all schools have been serving as homes for displaced individuals up to the time of this survey. Likewise, children residing in Syrian IDP camps lacked access to education [42].

In line with the findings of this study, the World Food Program (WFP) reported in 2022 that internally displaced individuals residing in areas without road access faced multiple crises following the armed conflict in Tigray [43]. During the crisis, armed conflict was the leading cause for people's death, injury, disability, and morbidity [44]. Similarly, a study conducted in Nigeria revealed that around 300,000 people were internally displaced due to armed conflict, with many of them relying on natural resources to support their living [45]. On a broader African scale, one in three nations experienced the impact of armed conflicts, accounting for 54.0% of recorded deaths and 53.1% of reported disabilities [44].

The armed conflict on Tigray resulted in a severe shortage of employment, leaving people unable to work or relocate, even on working days. According to Asgedom et al. [44], the armed conflict made it extremely challenging to engage in both agricultural and non-agricultural job activities, disrupting normal routines and seasonal farm operations. Similarly, Gebregziabher et al. [46] reported that the armed conflict on Tigray resulted in routine activities being either completely or partially disrupted. These challenges were further exacerbated by movement restrictions and limited access to farmlands, which severely hindered agricultural productivity. The decline in farm productivity and business transactions negatively affected both the supply and demand for goods and services [47]. Furthermore, limited labor mobility and poor market access resulted from blockades on essential services such as banking, transportation, energy, water, and healthcare [46]. Ultimately, these challenges left most people without jobs. Among the interviewees, 21 reported that their family members had been victims of rape perpetrated by military personnel during the armed conflict. Respondents noted that the primary targets of rape were spouses and daughters, particularly those associated with local militia or fighters. During the armed conflict on Tigray, rape was widespread, predominantly targeting young people and leaving significant psychological scars on the survivors [48].

Apart from these impacts, the armed conflict on Tigray severely disrupted agricultural performance [46]. For example, nearly 93.4% of households reported reducing their working hours due to the conflict. Furthermore, approximately 94.4% faced difficulties in accessing agricultural inputs, 74.1% lacked market access, 95.1% were unable to get informal financial services, and 94.7% experienced movement restrictions. The armed conflict resulted in a significant decline in crop cultivation, reaching critical levels, despite communities' efforts to sustain production [46].

The survey found that 61.8% of households experienced irrigation system damage, which diminished agricultural productivity. Congruent to this finding, a recent study by Meaza et al. [49] revealed that military

actors in Tigray looted valuable assets for military purposes, including pipes, irrigation pumps, water generators, and essential other supplies. About 65% of households reported that most of their livestock had been slaughtered, looted, or sold. With the loss of oxen and cattle, farmers in Abergelle-Yechila, Tigray, were forced to prepare their farmlands during the rainy season using camels and donkeys (see Fig. B2 in the appendix). This shows the adaptive, yet challenging, measures employed by local farmers in response to the armed conflict.

However, because these domestic animals were primarily used for local transportation during peacetime, they were rarely used for tilling croplands [49]. This highlights the devastating impact of the armed conflict on the livestock sector in Tigray. In addition, 44.7% of households reported losing farm equipment such as sickles, axes, shovels, yokes, hoes, and plow sphere. Nearly 78.9% of households indicated that the loss of these tools led to a complete loss of income during the armed conflict [46].

3.1.3. Conflict-induced reliance on woody vegetation

To assess the impact of the armed conflict on natural resource use, we compared the quantity and frequency of harvesting selected products, such as firewood, charcoal, and fodder, from woody natural vegetation before and after the armed conflict. Table 3 presents the average weekly consumption of firewood and charcoal by households. During the armed conflict, residents collected firewood from surrounding forests an average of 2.9 times per month, compared to 0.9 times per month during peacetime. The *t*-test results show that the average time required to gather firewood during the conflict was approximately 1.4 times longer than in the peace period. The armed conflict exacerbated the depletion of natural resources in Tigray, partly because local regulations and by-laws collapsed. In the Horn of Africa, where conflicts are frequent and sustainable energy alternatives are limited, local regulation violations often lead to the accelerated destruction of natural forests [50].

Before the armed conflict on Tigray, households consumed about 90 kg of firewood per week, but this increased to 114 kg during the conflict. A paired sample *t*-test revealed that firewood consumption during the conflict was significantly higher, with an average increase of 24 kg compared to peacetime. Focus group discussions and key informant interviews further revealed that firewood extraction increased dramatically during the armed conflict, as local bylaws and government regulations were disregarded. As noted by Meaza et al. [49], previously

Table 3
Fuelwood and fodder collection from natural vegetation during the armed conflict in selected districts of Tigray, Ethiopia.

Activities	Mean Values		Difference	<i>t</i> -test <i>t</i>
	Before the armed conflict	After the armed conflict		
Frequency of firewood collection per month (N)	0.9	2.3	1.4	4.52***
Quantity of firewood consumed weekly (kg)	90	114	24	5.04***
Quantity of charcoal consumed weekly (kg)	13.4	14.3	1.0	0.68
Quantity of dung burned weekly (kg)	14.1	10.5	−3.6	2.90***
Frequency of timber harvested per year (N)	1.6	2.9	1.3	2.72***
Frequency of grazing in forests (N)	5.7	11.3	5.6	1.76*
Quantity of fodder collected per year (kg)	108	102	−6	0.60

Notes: *N* = Number; Significance levels = *** $p < 0.001$, and * $p < 0.05$.

protected forest areas became accessible to all, resulting in unrestricted and competitive use of forest resources.

The indiscriminate harvesting of firewood, including the cutting of live trees, was also reported by Negash et al. [26]. FGDs and KIIs indicated that firewood was used not only for personal consumption but also for sale. At the start of the armed conflict, many individuals sought refuge in forests, hiding their animals and belongings, and the influx of displaced people from urban areas increased the demand for forest wood for shelter and fencing [49]. In the conflict-affected Tigray, where the two-year armed conflict resulted in a complete loss of electricity, forests have become the primary sources of energy and shelter for the local population [10].

The lawlessness and lack of accountability during the armed conflict led to extensive tree-cutting in areas like Abergelle-Yechila. Displaced individuals were involved in cutting trees for temporary shelters, gathering firewood, and collecting branches for animal feed, with some even traveling to distant forests for hunting [49]. According to a 46-years old key informant, full reliance on fuelwood resulted in a rapid depletion of forest resources. Similarly, the ongoing conflict in Syria, coupled with the absence of forest regulations, has fueled illicit logging by both locals and refugees living in neighboring forests [51].

3.1.4. Indirect consequences of armed conflict on livelihoods

Based on the findings, the armed conflict in Tigray severely undermined all five livelihood capitals. The engagement of active labor force in the armed conflict weakened the human capital in Tigray, mainly due to death, injury, and migration [44]. Education and health services also collapsed, resulting not only in poor productivity but also in a long-lasting brain drain [46]. Natural capital was heavily degraded as communities resorted to unsustainable extraction of fuelwood, charcoal, and timber from previously protected forests to meet their energy needs, leading to deforestation, land degradation, and depletion of vegetation resources [52]. Physical capital was severely affected, with widespread demolition of homes, looting of farm tools, and financial institutions. Strict movement restrictions further limited access to farms and essential services, effectively paralyzing agricultural production [49]. Financial

capital also declined sharply as household income from agricultural production, daily labor, and small businesses dwindled due to lack of markets and mobility.

On the other hand, remittances increased markedly in areas like Samre and Atsbi through informal transaction systems such as “hawala,” as access to formal banks and microfinance institutions was entirely halted. Social capital, however, was weakened as migration and poverty fragmented traditional structures, including cooperatives, associations, “idir” and “equb”. Religious leaders remained active, providing spiritual guidance, fostering social cohesion, and offering emergency support and limited aid. Overall, the armed conflict in Tigray destroyed livelihood foundations, forcing local communities to rely on unsustainable coping strategies [20], which threaten both short-term survival and long-term recovery of livelihoods and social assets.

3.2. Impact of armed conflict on natural resources

3.2.1. NDVI-based vegetation cover change detection

The impact of the armed conflict in Tigray on vegetation cover in the Abergelle-Yechila, Atsbi, and Samre watersheds was assessed using NDVI-based data, revealing substantial changes from January 2020 (pre-conflict) to January 2024 (post-conflict) (Fig. 2). In Abergelle-Yechila, vegetation coverage reduced from 1.4% in 2020 to 0.6% post-conflict, making a nearly 57% decline. This significant decrease reflects the armed conflict's severe environmental toll, likely driven by deforestation for survival, destruction from military activities, and the abandonment of agricultural lands. The loss underscores the direct relationship between armed conflict and environmental degradation in the region. Other contributing factors may include restricted access to agricultural inputs and disruptions in community-based conservation efforts.

In the Atsbi watershed, vegetation cover also declined though less significantly. It dropped from 9.2% to 8.2%, representing a reduction of approximately 10.9%. This smaller reduction suggests a lesser direct impact, possibly due to reduced combat intensity or fewer displaced populations compared to Abergelle-Yechila. Nevertheless, the loss

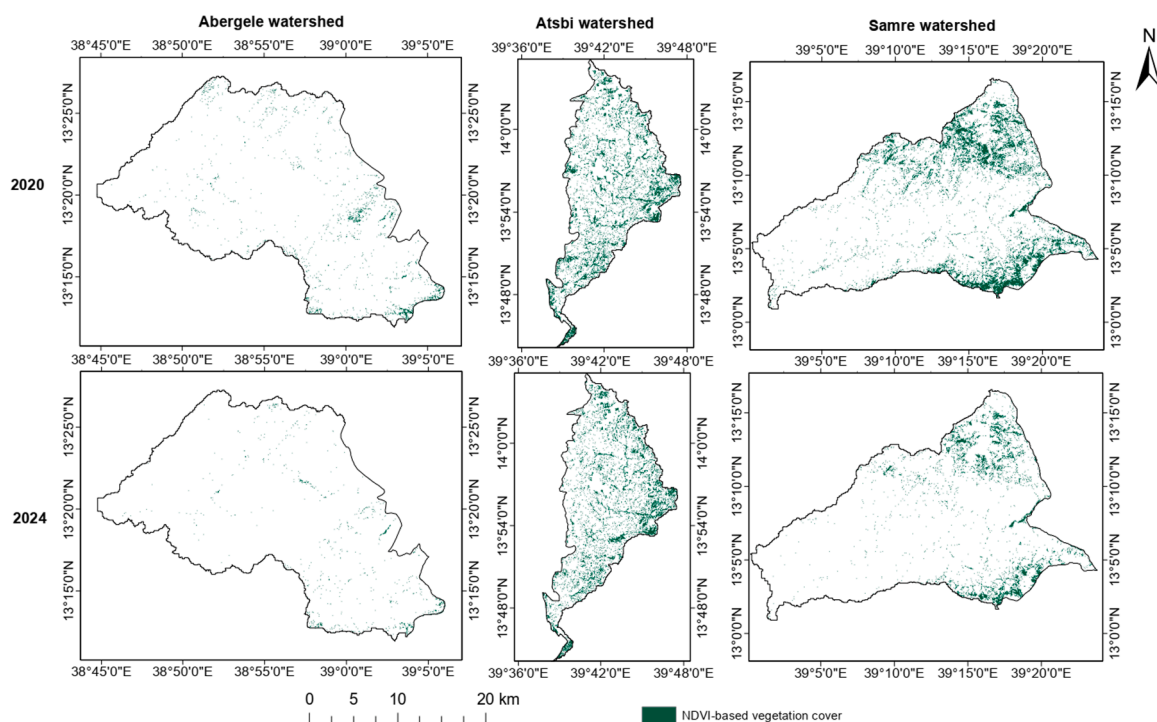


Fig. 2. NDVI-based vegetation cover maps for the Abergelle-Yechila, Atsbi, and Samre watersheds in January 2020 (before the armed conflict) and January 2024 (post-conflict).

indicates increased pressure on natural resources due to population displacement and heightened reliance on forest products for fuel and shelter. Additionally, reduced labor and financial resources for land management likely exacerbated the situation.

The Samre watershed experienced a severe decline in vegetation cover, dropping from 11.9% to 5.3%, a reduction of about 55.5%. This substantial loss highlights extensive environmental degradation, likely caused by intense combat, displacement-driven deforestation, and disruptions to local ecological restoration initiatives. This also indicates that the armed conflict likely exacerbated the vulnerability of these fragile ecosystems.

The analysis across the three watersheds clearly demonstrates the profound and detrimental impact of the armed conflict on NDVI-based vegetation cover. Negash et al. [26] also reported a regional decline in dry Afromontane forest cover in Tigray, from 17% in 2020 to 12% in 2022. Other similar studies have also documented significant vegetation losses due to conflict-driven environmental degradation on a global scale [51–54]. Field-based evidence further corroborates the NDVI-based assessment of vegetation damage in the watersheds. Observations at the plot level confirmed extensive vegetation loss in conflict-affected areas, particularly in Abergelle-Yechila, where deforestation and habitat destruction were especially severe. In contrast, Atsbi had relatively intact vegetation and regenerative potential, suggesting a lower impact compared to the other two watersheds.

The causes of vegetation loss during the armed conflict are multifaceted. Widespread deforestation occurs due to logging for fuel and shelter, while combat operations often involve intentional burning and clearing of forests. The resulting environmental degradation threatens local ecosystems and could affect agricultural productivity and disrupt water resources. The findings from these case study watersheds demonstrate that the armed conflict has reversed three decades of environmental rehabilitation efforts in Tigray, pushing the region back to its pre-restoration state within just two years of armed conflict. This collapse has intensified the environmental crisis, disrupted conservation initiatives, and left protected areas highly vulnerable to habitat destruction. Additionally, resource competition among displaced populations and weakened governance have further exacerbated the damage. Long-term rehabilitation in Tigray is crucial but faces significant challenges due to the scale of environmental destruction. Therefore, restoration efforts must prioritize reforestation, sustainable land management practices, and the reinforcement of natural resource governance to mitigate these impacts and foster socio-ecological resilience in the region.

3.2.2. Effects of distance from town on the number of harvested woods and vegetation cover

We recorded the distance of each sample plot in the enclosure areas from the nearby town, as well as the presence of IDPs, the duration of military presence, and the frequency of armed conflict in each district (Table 4), to assess their relative impact on wood harvesting and subsequent degradation.

In Abergelle-Yechila, there was a significant negative relationship between distance from town and the number of harvested woods ($p < 0.05$), explaining 76.6% of the variation (Table 5). This indicates that as the distance from towns increased, the number of harvested woods decreased. In contrast, in Samre, the relationship was weaker and not statistically significant ($p = 0.173$), explaining only 11.3% of the variation. Similarly, in Atsbi, no significant relationship was found ($p = 0.077$), with only 18.3% of the variation explained.

For vegetation cover, Abergelle-Yechila showed a significant positive relationship with distance from town ($p = 0.023$), with 28.5% of the variation explained (Table 5). In Samre, there was a significant negative relationship ($p = 0.001$), with 49.2% of the variation explained. In Atsbi, no significant relationship was observed ($p = 0.846$), with negligible variation explained.

The relationship between proximity to towns and vegetation

Table 4

Distance of sample plots from nearby towns, presence of IDPs and military personnel, and frequency of armed conflict in each district.

Variables	Abergelle-Yechila		Samre		Atsbi	
	Enda-kidane_Mihret	Qotslila	Adi-Azabie	Egamat	Dabir	Tseba ayna
Distance from town (km)	2	9	23	20	6	11
Presence of IDP	Yes	No	No	No	No	No
Frequency of armed conflict	3	3	2	2	1	1
Duration of Military Presence (months)	5	2	3	3	1	1

Table 5

Effects of distance from town on the number of harvested woods and vegetation cover across Abergelle-Yechila, Samre, and Atsbi districts.

Variable	Study site		
	Abergelle-Yechila	Samre	Atsbi
Number of harvested wood			
Coefficient	−1.70	−0.83	0.23
R ² (%)	76.6 (75.2)	11.3 (5.8)	18.3 (13.2)
p-value	<0.001	0.173	0.077
Vegetation cover			
Coefficient	2.05	−9.95	−0.32
R ² (%)	28.5 (24.0)	49.2 (46.0)	0.2 (0.0)
p-value	0.023	0.001	0.846

degradation is evident in the Abergelle-Yechila district, where intense harvesting closer to towns has led to more significant vegetation loss. These results align with findings in other conflict zones, where urban areas tend to experience higher pressure on natural resources due to increased human activity and military occupation [55].

3.2.3. Damage to vegetation in the study districts

In Abergelle-Yechila, 56% of the surveyed plots experienced full destruction, while 39% sustained partial damage, and only 5% were not damaged. In the Atsbi district, 77.8% of the plots were partially damaged, with 22.2% showing no damage. Similarly, in the Samre district, 72.2% of the plots experienced partial damage, and 28.8% were fully damaged. These findings indicate a significant level of vegetation degradation in all districts, which can be attributed to the prolonged armed conflict and its direct impact on natural resources. The results underscore the profound toll that such conflicts have on local landscapes, with forests and vegetation being severely impacted. Fig. 3 illustrates some selected damages on woody vegetation in the study districts.

In Abergelle-Yechila, 165 dead and damaged species were recorded, averaging 9 per plot, resulting in 40% damage or 225 trees per hectare. Human activities, including harvesting by local communities, internally displaced persons (IDPs), and military personnel, were responsible for 95% of the damage, with only 5% attributed to natural causes. Commonly damaged species included *Dichrostachys cinerea* Brenan & Brummitt (25.6%), *Vachellia abyssinica* (Hochst. ex Benth.) Kyal. & Boatwr (25.6%), and *Vachellia etbaica* (Schweinf.) Kyal. & Boatwr (14%). In Atsbi, 56 damaged species were noted, with an average of 3 woody species per plot, resulting in a 16% loss, or 75 trees per hectare. 99% of the damage was caused by the community, with *Juniperus procera* (46.4%) being the most affected species. In Samre, 125 damaged trees were recorded across all plots, with an average of 7 trees per plot, totaling a 37% loss. *Vachellia etbaica* (58.4%) was the most damaged

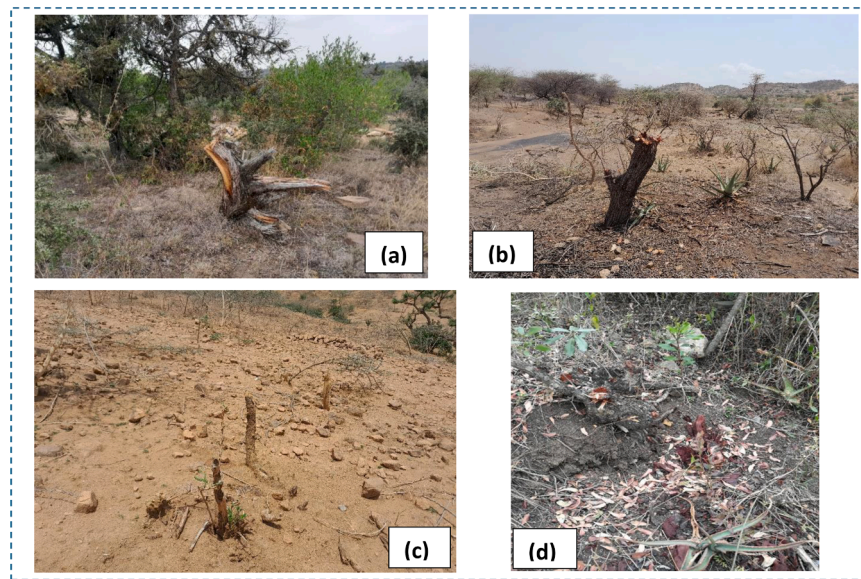


Fig. 3. Examples of damage to woody vegetation species in selected districts of the Tigray region: (a) Atsbi, (b, c) Abergelle-Yechila, and (d) Samre.

species. Almost all of the damage (99%) was caused by military personnel and the community.

These findings highlight the significant role of human activities, particularly those of local communities and military personnel, in vegetation destruction. Similar studies in armed conflict zones, including those by Negash et al. [26] and Hishe et al. [10], reported similar patterns of vegetation loss due to the collapse of fuel supply systems, which forced communities to rely on local forests for firewood during conflicts.

The study revealed significant differences in harvested wood and vegetation cover across Abergelle-Yechila, Samre, and Atsbi. The average harvested wood per plot was highest in Abergelle-Yechila (9.00 ± 1.70), followed by Samre (6.94 ± 0.71), and lowest in Atsbi (1.55 ± 0.32) (Fig. 5). The differences were statistically significant ($p = 0.000$), indicating notable variation in wood harvesting among the sites. Vegetation cover (%) also varied significantly ($p = 0.006$). Atsbi recorded the highest vegetation cover ($41.72 \pm 3.82\%$), followed by Samre ($34.44 \pm 4.73\%$), and Abergelle-Yechila ($22.64 \pm 3.37\%$) (Fig. 4). These findings demonstrate an inverse relationship between harvested wood and vegetation cover, with sites experiencing higher wood harvesting generally exhibiting lower vegetation cover.

Table 6

Comparison of harvested wood and vegetation cover across exclosures of each district.

Variables	Study sites		t- value	p- value
	Abergelle-Yechila			
	Enda-Kidane Mihret	Qotslila		
Harvested woods	15.1 ± 1.5	2.89±0.86	6.96	0.000
Vegetation cover (%)	15.2 ± 2.1	30.0 ± 5.5	-2.50	0.032
	Samre			
	Adi-Azabie	Egamat		
Harvested woods	5.56±0.96	8.33±1.2	-1.79	0.094
Vegetation cover (%)	20.0 ± 2.5	48.9 ± 6.1	-4.41	0.001
	Atsbi			
	Dabir	Tseba ayna		
Harvested woods	1.0 ± 0.47	2.11±0.39	-1.82	0.089
Vegetation cover (%)	42.8 ± 5.0	40.7 ± 6.1	0.27	0.792

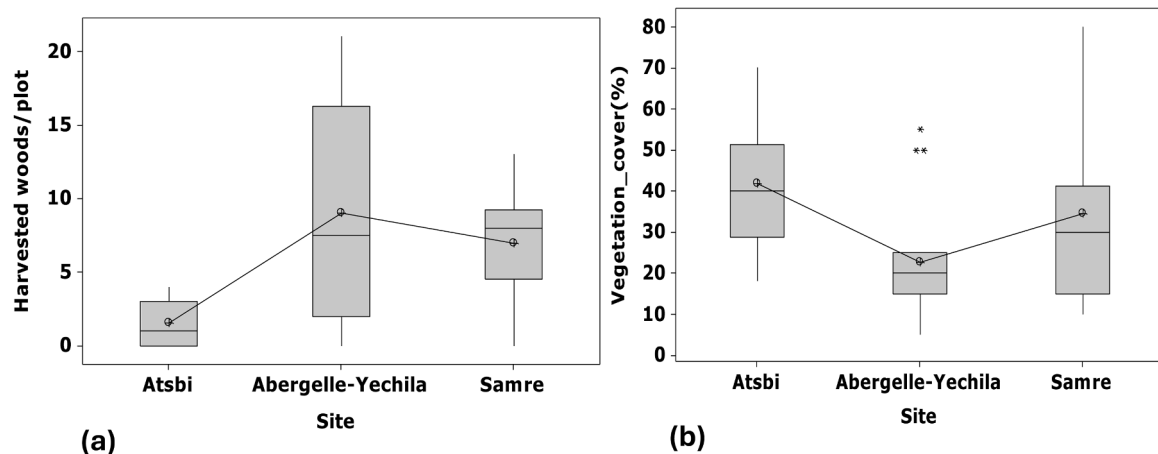


Fig. 4. Quantity of harvested wood per plot (a), and vegetation cover percentage (b) in Abergelle-Yechila, Samre, and Atsbi districts.

The findings on harvested wood and vegetation cover reveal notable differences across Abergelle-Yechila, Samre, and Atsbi (Table 6). In Abergelle-Yechila, the quantity of harvested wood was significantly higher in Enda-Kidane Mihret compared to Qotslila, with a significant difference (t -value = 6.96, p = 0.000). Conversely, vegetation cover was significantly greater in Qotslila than in Enda-Kidane Mihret (p = 0.032). In Samre, the mean harvested wood was higher in Egamat compared to Adi-Azabie, but this difference was not statistically significant (p = 0.094). However, vegetation cover was significantly greater in Egamat than in Adi-Azabie (p = 0.001). In Atsbi, Tseba ayna recorded a higher mean quantity of harvested wood compared to Dabir, but the difference was not statistically significant (p = 0.089).

These results echo the findings of other studies on land degradation and the impacts of conflict on forest cover. For example, studies in Ethiopia, including the work by Bekere et al. [56], have shown that conflict exacerbates land degradation, resulting in increased deforestation and the loss of biodiversity. The higher levels of vegetation cover in Atsbi suggest that the community in this district may have been less reliant on the forest for fuel compared to Abergelle-Yechila and Samre.

Overall, the significant vegetation degradation observed in the study districts highlights the extensive environmental toll of the armed conflict in the Tigray region. This degradation is largely driven by human activity, including harvesting by communities, internally displaced persons, and military personnel, as well as the collapse of fuel supply systems, forcing communities to rely on local forests. Similar patterns have been documented in other conflict-affected regions such as the Democratic Republic of the Congo and Sierra Leone [55], where wars have resulted in extensive deforestation and further exacerbated humanitarian crises. In Tigray, the loss of public services has pushed communities to adopt unsustainable practices, exacerbating forest degradation [26].

Among the studied districts, Abergelle-Yechila expectedly faced the most severe vegetation damage among the districts due to its role as a battleground, prolonged military presence, and displacement influx, followed by Samre, impacted by the occupation of Eritrean troops. Surveys from Abergelle-Yechila, Atsbi, and Samre demonstrate the profound impact of the armed conflict on forests, aligning with broader Ethiopian trends. Negash et al. [26] reported a decline in Tigray's dry Afromontane forest cover from 17% in 2020 to 12% in 2022, and Hishe et al. [10] noted a 5% vegetation cover loss (403 km²) over the same period. The Conflict and Environment Observatory linked vegetation loss to reliance on forests for firewood amid fuel shortages [57]. Similar patterns of deforestation and degradation have been documented in Ethiopia [56,58] and globally, including in the Democratic Republic of the Congo and Liberia [55,57]. Conflicts exacerbate land degradation, biodiversity loss, and soil erosion, driven by socio-political instability and climate variability [59,60]. Overall, the armed conflict on Tigray has undone years of restoration efforts, underscoring the cyclical link between conflict and environmental degradation [61]. This is consistent with broader research on the cyclical relationship between violent conflicts and environmental degradation, where the destruction of natural resources during conflict undermines the resilience of local communities and their ability to recover post-conflict. Moving forward, it will be crucial to integrate conflict-sensitive approaches into environmental restoration efforts to ensure the sustainable recovery of landscapes affected by the armed conflict.

3.2.4. Impact of the armed conflict on nursery resources

The armed conflict has had a devastating impact on nursery resources, severely disrupting essential assets for ecological restoration and hindering environmental conservation efforts. Nursery sites in the Abergelle-Yechila, Atsbi, and Samre districts suffered extensive damage, including the destruction of infrastructure, equipment, and seedlings. In Abergelle-Yechila, the nursery experienced an estimated loss of USD 5,175.25 (based on an average exchange rate of 40 ETB per USD between 2020 and 2022) due to looting and destruction by military

personnel and illegal actors. Essential tools such as hoes, rakes, levels, tables, and balances were either damaged or stolen, leaving the site unable to maintain or cultivate seedlings. This has drastically reduced the nursery's productivity, rendering it unsustainable.

The Atsbi nursery site lost approximately 99,500 seedlings, resulting in an estimated loss of USD 12,437.50. Before the armed conflict, the nursery had sufficient inputs like seeds and pesticides, ensuring effective seedling production. However, post-conflict shortages of these critical inputs have significantly restricted their operations. Although the site was not looted and remains functional, the lack of essential resources poses serious challenges, threatening its capacity to support reforestation and environmental restoration efforts.

Similarly, the Samre nursery was completely devastated, with material losses estimated at 3,278.50 USD. The destruction of equipment and infrastructure has left the site entirely non-operational, leading to its transfer to private ownership. While this transfer offers some potential for revival, the extent of the damage presents considerable obstacles to restoration.

The widespread destruction of nursery resources underscores the severe impact of the armed conflict on reforestation and environmental conservation initiatives. The loss of seedlings, tools, and infrastructure constitutes not only a significant financial setback but also a major disruption to efforts aimed at mitigating environmental degradation. Addressing these challenges calls for urgent and sustainable recovery strategies to restore nursery operations and advance ecological restoration in the region.

3.3. Impacts on soil-water conservation measures

3.3.1. Conflict-induced damage to soil and water conservation structures

Over the past 2 – 3 decades, various soil and water conservation (SWC) practices have been implemented in the Atsbi, Samre, and Abergelle-Yechila watersheds of Tigray, Ethiopia, with support from the government, NGOs, and active community participation [62]. These include physical structures like stone bunds, terraces, basins, check dams, and trenches, along with biological measures such as exclosures and tree plantations. Stone bunds, common in stone-rich areas, are built along contours to retain water, trap sediment, and reduce runoff, enhancing infiltration (Fig. 5).

Before the armed conflict, hillside terraces were constructed on the mountainsides of Atsbi, specifically designed for areas with steep slopes where stone bunds would be unstable due to the gradient. These terraces were spaced closely (2–3 m apart) to effectively prevent soil erosion caused by wind and water on the hillslopes [63]. Similarly, in Abergelle-Yechila and Samre, bench terraces were created by moving earth and stones to transform sloped areas into flat benches suitable for agriculture. These terraces served multiple purposes, such as controlling runoff, conserving soil, and providing arable land. Additionally, half-moon (micro-basin) structures were established for both soil and water conservation and tree planting. The staggered arrangement of these structures maximized the interception of surface runoff and sediment. The runoff storage towards the center of the micro-basin created ideal conditions for planted trees, increasing their chances of survival. The combination of micro-basins with trees or grasses has proven to be an effective conservation strategy, promoting both conservation and productivity, such as fruits, fodder, and grasses, and transforming degraded landscapes into productive areas.

However, these soil and water conservation (SWC) structures were severely damaged during the armed conflict on Tigray. Reports show that conflict-induced environmental damage can have both direct and indirect impacts [64]. Direct impacts include activities like tree cutting or deforestation, while indirect impacts involve land degradation and soil erosion. Likewise, many of the SWC structures in the study sites were damaged by both military forces and local communities. Similar destruction of conservation structures has been reported in Ukraine, where military actions have damaged water infrastructure such as dams

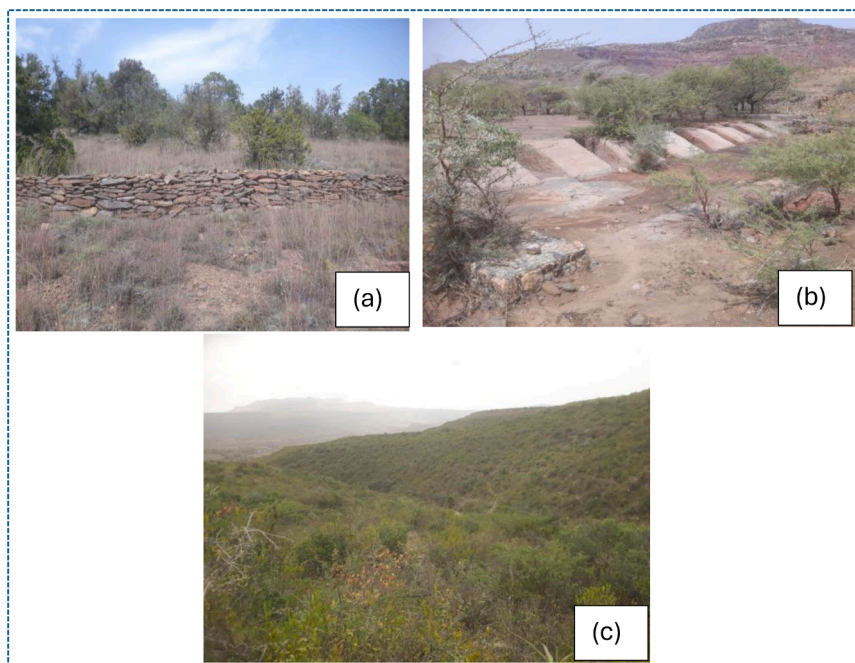


Fig. 5. Examples of soil and water conservation practices in selected watersheds: (a) stone bunds in Atsbi, (b) river diversion in Abergelle-Yechila, and (c) biological conservation in Samre.

and supply systems, disrupting sustainability efforts and hindering access to clean water, conservation, and food security [8].

In Samre and Abergelle-Yechila, stone bunds were destroyed by both local communities and the troops stationed in the area. Many of these structures, especially in Abergelle-Yechila and Samre, were repurposed as fortifications and burial sites (Fig. 6). Soldiers used the half-moon structures and stone bunds as fortifications. After the breakout of the armed conflict, the community also violated the bylaws governing enclosures, allowing cattle to graze in protected areas, which further damaged the SWC structures.

3.3.2. Soil erosion

We assessed the impact of the armed conflict on soil loss using the Revised Universal Soil Loss Equation (RUSLE). Table 7 presents a summary of the annual soil loss before (2020) and after (2023) the armed conflict.

As shown in Table 7, soil erosion has significantly increased following the prolonged armed conflict in these districts, with annual losses rising from 7.2 to 11.2 tons per hectare in 2020 to 8.1–15.6 tons per hectare by 2023. The destruction of soil conservation structures and the increased deforestation rate have exacerbated this issue. While all

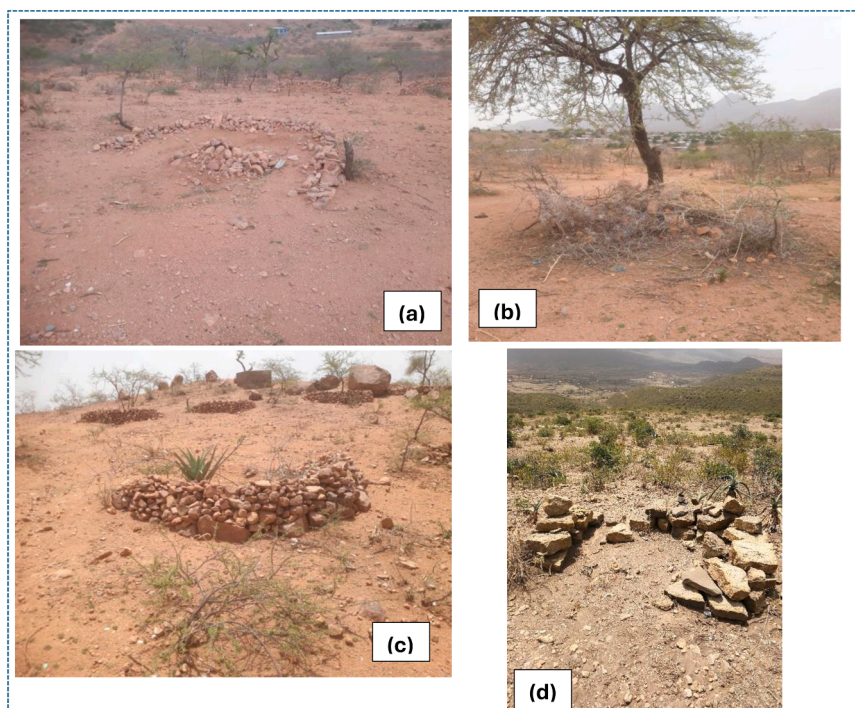


Fig. 6. Transformation of soil and water conservation structures into fortifications and burial sites: (a-c) Abergelle-Yechila and (d) Samre.

Table 7

Annual soil loss before (2020) and after (2023) the armed conflict.

S/ N	Watersheds	Area in ha	Soil loss in 2020 tons/ ha/ year	Soil loss in 2023 tons/ ha/ year	Soil loss increment from 2020 to 2023 tons/ ha/year	Soil erosion rate (severity)
1	Atsbi	28,054	7.2	8.1	+0.9	Moderate
2	Samre	59,344	10.0	15.5	+5.5	High
3	Abergelle- Yechila	55,347	11.2	15.6	+4.4	High

watersheds saw an increase in soil erosion in 2023, Abergelle-Yechila and Samre experienced particularly high increases.

These findings align with regional and international studies. For instance, in the Al-Kabeer River Basin of Syria, approximately 79.9% of observed soil erosion was linked to conflict-induced disturbances [65]. Within Ethiopia, recent assessments have also reported alarming trends. Similarly, the Lake Ziway watershed recorded average soil losses exceeding $40 \text{ t ha}^{-1} \text{ yr}^{-1}$ between 1993 and 2023, well above the national tolerable threshold of $10 - 15 \text{ t ha}^{-1} \text{ yr}^{-1}$ [66]. In the Upper Tekeze Basin, Ethiopia, average soil erosion rates reached $25.5 \text{ t ha}^{-1} \text{ yr}^{-1}$, with 63% of the area surpassing the tolerable limit. Notably, unprotected shrublands, which constitute 55% of the basin, experienced erosion rates as high as $34.75 \text{ t ha}^{-1} \text{ yr}^{-1}$ [67]. A nationwide synthesis of soil erosion studies reported an average gross erosion rate of $38 \text{ t ha}^{-1} \text{ yr}^{-1}$, though values vary considerably across agro-ecological zones and assessment methodologies [68]. These reports collectively reinforce the consistency and validity of the present findings, which align with broader patterns of environmental degradation observed across Ethiopia.

Notably, unprotected shrublands, covering 55% of the basin, showed a loss rate of $34.75 \text{ t ha}^{-1} \text{ yr}^{-1}$ [67]. A comprehensive review of Ethiopian soil erosion studies revealed national average gross soil erosion rates of 38 t/ha/yr , with significant variations across agro-ecological zones and assessment methods [68]. This demonstrates the consistency of our findings with other similar studies conducted at local scales, particularly within the context of the Ethiopian landscape. Furthermore, hotspot areas have been delineated, and the severity of soil erosion has been prioritized across watersheds (Table 8). The most pronounced impact of conflict on soil erosion is evident in the Samre and Abergelle-Yechila watersheds, where erosion severity shifted from slight to moderate in 2020 to moderate to high by 2023. The increase in soil loss across all watersheds highlights the urgent need for restoration and the re-establishment of SWC infrastructure in the conflict-affected areas.

The soils are highly vulnerable to erosion due to several factors, including intense fighting over the watersheds, hilly terrain, poor soil quality (characterized by fine texture, low organic matter, and limited plant cover due to the semi-arid climate), and inappropriate agricultural practices such as excessive tillage and cultivation on steep slopes. These findings have been confirmed by previous studies. Armed conflict often leads to the destruction of vegetation, which plays a critical role in maintaining soil stability. The disruption of sustainable land management practices, combined with increased deforestation, accelerates soil

Table 8

Soil erosion risk classes based on soil loss rate (tons/ha/year).

S/ N	Soil loss t/ha/ yr	Soil erosion severity in 2023	Watersheds
1	0–1	Very slight	-
2	1–5	Slight	-
3	5–15	Moderate	Atsbi
4	15–30	High	Samre and Abergelle- Yechila
5	30–50	Severe	-
6	>50	Very severe	-

erosion, resulting in reduced agricultural productivity and land degradation.

During our visits to the Abergelle-Yechila and Samre watersheds, we observed substantial damage to vegetation, which could potentially worsen soil erosion [69,70]. A similar study by Hishe et al. [10] reported that the armed conflict in Tigray resulted in a 5% reduction in vegetation cover, further contributing to land degradation. The loss of vegetation has exacerbated soil erosion, leading to a decline in land fertility and reduced agricultural output. Similarly, in Sudan, extensive soil erosion caused by conflict has reduced agricultural yields and heightened food insecurity [14].

Almohamad [65] reported that in the Al-Kabeer river basin in Syria, conflict led to significant vegetation loss, which in turn increased soil erosion rates. The removal of plant cover exposes the soil to erosion by wind and water. Additionally, military operations can disrupt soil structure, causing compaction and increasing erosion. A study by Kheir et al. [71] in Lebanon found that military activities significantly altered soil properties, increasing their susceptibility to erosion.

Given these findings, it is essential to prioritize and continue land and water management efforts in high-risk areas, especially in Abergelle-Yechila and Samre, which have experienced prolonged armed conflict. While the implementation of soil and water conservation measures has shown promise in reducing soil erosion rates, further strategic planning is necessary to minimize soil loss in the watershed, aiming to keep it below the maximum tolerable soil loss rate.

3.4. Recovery efforts and their sustainability

We investigated post-conflict natural resource recovery efforts in the three selected districts of Tigray, focusing on both formal initiatives and community-driven approaches, particularly in areas where military forces had been stationed for extended periods during the conflict. Our assessment evaluated the effectiveness and sustainability of these efforts in restoring and conserving natural resources. Despite the armed conflict's devastating impact on decades of soil and water conservation initiatives, there has been notable voluntary participation from local communities in post-conflict recovery efforts (Fig. 7).

For instance, in the Atsbi and Samre watersheds, significant steps have been taken to initiate post-conflict reconstruction by repairing crumbled structures and mobilizing community support. New soil and water conservation measures have also been implemented in these areas. Deep trenches have been constructed along the watersheds to capture water, reduce runoff, conserve soil, and enhance land suitability for cultivation (Fig. 7). These trenches feature contour barriers consisting of ditches and earthen embankments. Conservation trenches are typically 0.5 m wide, 0.5 m deep, and 3 m long, while infiltration trenches may reach depths of up to 2 m. Successive trenches along the contour are separated by 0.6-meter earthen barriers, resembling tied ridges to enhance their functionality.

Furthermore, in the Atsbi watershed, we have also observed newly constructed check dams along the degraded gullies (Fig. 7). These barrier structures are built across the gullies to block runoff and sediment transport within the gully system. The check dams are constructed from loose stones (loose stone check dams), gabions, and brushwood. Utilizing check dams to address gullies is a crucial method for reducing soil erosion, controlling sediment transport, and harvesting water for irrigation or groundwater recharge. In contrast, the Abergelle-Yechila watershed, despite having chem dams constructed before the armed conflict, has seen limited implementation of soil and water conservation measures during the post-conflict recovery phase. This disparity underscores the need for equitable and coordinated recovery efforts to ensure sustainable resource management across different regions.

These post-conflict restoration efforts are promising but require a more integrated approach that encompasses diverse measures and fosters collaboration. Combining physical soil and water conservation techniques with biological measures has proven to be more effective and



Fig. 7. Post-conflict soil and water conservation efforts in selected watersheds: (a) check dams in Atsbi, and (b) deep trenches in Atsbi, (c) Abergelle-Yechila, and (d) Samre.

sustainable for landscape rehabilitation than relying solely on physical methods. To ensure long-term success, it is essential to engage all relevant stakeholders in a cohesive and integrative effort.

Localized recovery initiatives, such as those in Atsbi, have achieved progress through the reinstatement of traditional regulations and active community participation. However, broader recovery efforts continue to be impeded by fragmented and poorly coordinated management strategies. This underscores the urgent need for integrated and comprehensive approaches. Community-driven initiatives and indigenous knowledge have demonstrated significant potential for recovery, but effectively addressing these complex challenges demands greater collaboration and strategic alignment among all stakeholders.

The study further evaluated households' willingness to contribute to tree plantation and conservation practices. The willingness to pay for seedlings was quantified in Ethiopian Birr (ETB), while the number of labor days households were willing to offer voluntarily for conservation efforts was also recorded. The findings reveal that households are willing to actively engage in natural resource restoration by providing both financial and labor support, particularly for seedling planting and soil and water conservation initiatives (Table 9). Approximately 91% of respondents expressed readiness to cover costs associated with environmental recovery, including expenses for tree planting and conservation structures, with an average willingness to contribute 35 Ethiopian birr (ETB) per month. Similarly, about 90% of households

indicated that they are willing to participate in afforestation efforts, with an average willingness to spend 48.1 ETB on purchasing seedlings. In addition to financial contributions, farm households showed willingness to provide an average of 4.92 labor days for tree planting and 7.2 labor days for soil and water conservation activities on communal lands (Table 9).

The results also found that, among the three study sites, conservation efforts to reduce forest destruction were carried out by churches, concerned individuals, and NGOs, particularly in Atsbi district (*Woreda*). Church members played a key role in forest protection by persuading both the local community and military personnel. Priests emphasized the sacredness of forests, preaching that "Forests are sacred places where angels and God communicate." They also reminded the community of the long history of life supported by forests. As a result, priests and local communities reached an agreement to refrain from cutting down trees. Additionally, priests engaged with military officers to discuss the problem of forest destruction. This finding is consistent with that of Gitonga et al. [72], who found that the Church contributed to environmental conservation in Kenya by educating communities on the advantage of tree planting, promoting environmental conservation practices among Christians, and discouraging tree cutting, among other practices. Besides, our results are also in agreement with the findings of Jerie [73], who reported successful church-based natural resource management projects in Zimbabwe, which result in improved use of forest resources in the country. Furthermore, Tilahun et al. [74] revealed that The Ethiopian Orthodox Tewahido Church has made substantial contributions to forest management.

Our study found that NGOs (e.g., WeForest) also contributed to forest protection by implementing various conservation efforts, even during the armed conflict. According to FGD and KII participants, WeForest worked to mobilize local people for tree planting by providing seedlings during the armed conflict. These results reflect those of Neba [75], who also found that NGOs played a pivotal role in environmental protection and significantly impacted the socio-economic and political condition of the communities. However, Neba [75] questioned the sustainability of the roles NGOs play as they highly depend on other funds.

Additionally, other concerned farmers have been planting seedlings

Table 9
Households' willingness to participate in natural resource recovery efforts.

Indicators	Observation	Mean	Standard Deviation
willingness to pay for restoring the environment	276	0.91	0.29
Maximum monthly payment	289	35.1	57.61
Willingness to pay for afforestation	276	0.90	0.29
Maximum payment for buying seedlings	274	49.7	83.87
Labor days for plantation	281	4.92	5.24
Labor days for soil and water conservation	302	7.4	8.29

around gullies and Churches, areas less likely to be damaged by animals. In Atsbi district, several households have established eucalyptus plantations, primarily for fuelwood consumption and timber sales. This practice contributes to both household livelihoods and the restoration of forest resources (see Fig. B3 in the appendix). In line to this finding, Ramadhani et al. [76] reported that farmers in Tanzania used rotational woodlots to generate substantial income by conserving forest areas.

The community strongly affirms that local participation is vital for effective soil and water conservation. They emphasize the inclusive involvement of all members, including persons with disabilities, who can actively contribute to environmental restoration through green livelihood activities. These include beekeeping, honey processing, composting organic waste, producing animal feed, livestock fattening, cultivating commercial timber species such as eucalyptus, and managing natural resources. To facilitate the participation of landless individuals with disabilities, the allocation of communal lands was identified as a key enabling strategy. This approach is intended to enhance their involvement and empower them to actively contribute to natural resource rehabilitation. Before the land allocation, the community plans to implement soil and water conservation measures on the designated lands to establish a strong ecological foundation for restoration efforts.

Another important finding is that farmers are unlikely to adopt environmental recovery techniques unless they perceive the benefits to outweigh the drawbacks. Since households are directly involved in various land use activities, such as cultivating crops, raising animals, producing fruits, growing timber, and utilizing forests, they are aware of the issues affecting land resources and the methods for producing and managing land effectively. To ensure effective environmental restoration, it is crucial to assess farmers' willingness to engage in various conservation measures and their understanding of the specific characteristics and conditions of their land. This requires involving the local community in all stages of conservation efforts, including planning, implementation, and decision-making. Increased involvement of households in restoration decisions fosters a stronger sense of ownership among community members and enhances communication with experts and government officials. In this regard, our study recommends that interventions that consider local willingness are crucial for achieving sustainable recovery of natural resources. Similarly, Tschakert [77] recommended the need for adequate and equitable financial support and a careful rethinking of the institutional structures necessary to enhance rural livelihoods and natural resource management.

Economic degradation, limited financial resources, disrupted infrastructure, and weakened public services are among the primary challenges faced in post-conflict situations. These challenges, compounded by poor governance and lawlessness, have led to the overexploitation of natural resources and widespread environmental degradation. Therefore, restoring natural resources in post-conflict contexts is essential and requires the development of strategies and mechanisms for rehabilitating and managing the affected environment [78]. Addressing post-conflict crises requires revising local environmental policies and restoring ecosystems through reforestation and afforestation. It also involves implementing soil and water conservation measures, strengthening the management of protected areas (exclosures), improving water resource availability, promoting sustainable alternative livelihoods, and ensuring robust institutional support. These measures serve as key mechanisms for restoring natural resources in post-conflict areas. Mitigating post-conflict natural resource damage demands a coordinated approach encompassing environmental assessment, sustainable management practices, community participation, and capacity building. Effective mitigation efforts require integrating environmental, social, and economic activities. Multi-stakeholder partnerships are crucial, involving collaboration among governments, international organizations, NGOs, and local communities. Such partnerships harness the strengths and resources of diverse actors to address complex post-conflict challenges comprehensively. Existing post-conflict ecological restoration strategies to mitigate natural

resource damage include a wide range of activities, such as environmental assessment, sustainable resource management, community engagement, and capacity building.

Our findings suggest that post-conflict ecological restoration strategies play a crucial role not only in rehabilitating natural resources but also in improving agricultural productivity, including crop yields and livestock performance [78]. Restored ecosystems contribute to diversified income sources by improving soil fertility, enhancing water availability, and promoting the growth of fodder and other non-timber forest products [15]. As the environmental base and farm productivity improve, rural communities are better positioned to engage in off-farm and non-farm income-generating activities, facilitating access to improved agricultural technologies and stronger market linkages for both inputs and outputs. In the context of post-conflict Tigray, such integrated restoration efforts are vital for strengthening rural livelihoods and enhancing the adaptive capacity of farm households to confront both post-conflict challenges and climate change risks [24].

The resilience of the socio-ecological system (SES) in Tigray was severely undermined by the armed conflict, with profound disruptions across ecological, institutional, and livelihood dimensions. Key drivers of resilience, such as natural capital (forests, soil, and water), physical capital (tools, infrastructure), and institutional structures (bylaws, community governance), were either weakened or destroyed. Vegetation covers sharply declined due to increased fuelwood harvesting, displacement-driven deforestation, and the collapse of regulatory frameworks, particularly in Abergelle-Yechila and Samre districts. Soil and water conservation structures were widely damaged, and nurseries critical for ecological restoration were looted or rendered inoperable. Human capital eroded through death, displacement, and the collapse of education and health services, while social capital was fragmented, despite some support from religious institutions. Nevertheless, pockets of resilience persisted, most notably in Atsbi, where stronger local by-laws, informal financial flows (e.g., *hawala*), and partially intact conservation structures helped buffer the worst impacts. These findings highlight that socio-ecological system resilience in conflict zones depends not only on ecological conditions but also on the strength of local governance, institutional continuity, and adaptive community responses.

Despite applying an SES framework to examine conflict-related impacts in Tigray, important knowledge gaps remain regarding the resilience of socio-ecological systems and the drivers that sustain or undermine it in post-conflict environments. This study demonstrated severe disruptions to vegetation cover, soil integrity, and community livelihoods, emphasizing the complex interplay between ecological degradation and socio-economic vulnerabilities. However, a key limitation lies in the lack of longitudinal and comparative SES analyses across varying conflict intensities and governance contexts. The current research relies heavily on snapshot assessments of change (e.g., NDVI and RUSLE from 2020 to 2024), which, while valuable, do not fully capture the long-term adaptive capacity and feedback mechanisms that define SES resilience. Moreover, while local bylaws and community action showed promise in mitigating damage in Atsbi, there is limited empirical understanding of how such institutional drivers function under stress and evolve. The heterogeneity observed across districts also highlights a broader gap in identifying which SES components (e.g., ecological condition, institutional strength, livelihood diversity) are most critical for resilience under conflict conditions.

Future research should integrate time-series SES data with institutional and governance assessments to monitor recovery trajectories and identify resilience thresholds. This is particularly urgent in conflict-prone or resource-scarce regions like Tigray, where both ecological and social systems remain fragile and co-dependent. Addressing these gaps is essential for developing more nuanced, context-sensitive recovery strategies that can endure future shocks.

4. Conclusion

The armed conflict on Tigray has inflicted severe damage on the natural resources and community livelihoods. Key findings of the study highlight that the armed conflict caused extensive damage to the natural resources in the selected case studies, including deforestation, soil erosion, and the collapse of local environmental restoration practices. The armed conflict has also induced widespread displacement, disrupted livelihoods, and led to unsustainable exploitation of natural resources. Despite some localized recovery efforts, such as those in Atsbi, which benefited from the reinstatement of local regulations and community involvement, overall recovery has been hindered by fragmented and poorly coordinated management strategies. Community-driven initiatives and indigenous knowledge have demonstrated potential for successful recovery, but a more coordinated approach is needed to address these complex issues effectively.

Future restoration should build on past successes, with a focus on immediate actions like enforcing local regulations, introducing alternative energy, and engaging communities. Medium-term strategies should promote sustainable practices and secure funding for large-scale restoration, while long-term efforts must institutionalize grassroots knowledge and integrate Farmer Managed Natural Regeneration (FMNR) with other sustainable practices. Further studies in other districts of the region, with consideration to wildlife, health impacts, and illegal mining are necessary to have a complete picture of the conflict-induced impacts. Overall, a coordinated approach that includes ecosystem restoration, capacity building, and environmentally friendly livelihoods is essential for sustainable recovery in post-conflict Tigray.

Ethical statement

This study was reviewed and approved by Mekelle University Community Engagement and Industry Linkage Directorate Office with the approval reference number CEIL-111/2024, dated 27/05/2024. An informed consent was also obtained from participants before they participated in this study.

Appendix A

Mekelle University, Ethiopia

Consent Form for Participation in a Research Study

The Impact of War on Socio-ecological Systems and the Sustainable Recovery of Natural Resources in Tigray, Ethiopia

You are invited to participate in **the research study** on The Impact of War on Socio-ecological Systems and the Sustainable Recovery of Natural Resources in Tigray, Ethiopia. You will be asked to mention how the war in Tigray has impacted ecological systems, livelihoods, social capitals and restoration efforts done by rural communities.

Time Involvement: Your participation will take approximately 45 min.

Protection of Confidentiality: The information that you give in the study will be handled confidentially. Your information will be assigned a code number. The list connecting your name to this code will be kept in a locked file. When the study is completed and the data have been analyzed, this list will be destroyed. Your name will not be used in any report.

Payments: You will receive Birr 100 as payment for your participation of time compensation.

Participant's Rights: If you have read this form and have decided to participate in this project, please understand your **participation is voluntary** and you have the **right to withdraw your consent or discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled**. You have the right to refuse to answer particular questions. The results of this research study may be presented at scientific or professional meetings or published in scientific journals.

Contact Information

If you have any questions, concerns or complaints about this research, its procedures, risks and benefits, contact the Researcher (Name: Zenebe Girmay and email: zenebegirmay@gmail.com).

Agreement

I agree to participate in the research study described above.

Signature: _____ **Date:** _____

CRediT authorship contribution statement

Emiru Birhane: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Zenebe Girmay Siyum:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Henok Shiferaw:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Negasi Solomon:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Melaku Berhe:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mewcha Amha Gebremedhin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Zbelo Tesfamariam:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix B

Table B1

Socio-demographic characteristics of respondents (N is the number of respondents).

Variable	Study districts							
	Abergelle-Yechila		Samre		Atsbi		Total	
	N (103)	%	N (101)	%	N (101)	%	N (305)	%
Sex								
Male	83	80.6	55	54.5	68	67.3	206	67.5
Female	20	19.4	46	42.6	33	32.7	99	32.5
Age								
15–29	14	13.6	14	13.9	7	6.9	35	11.5
30–64	79	76.7	82	81.2	79	78.2	240	78.7
≥65	10	9.7	5	5.0	15	14.9	30	9.8
Marital status								
Single	0	0	1	0.99	1	0.99	2	0.6
Married	100	96.1	83	82.2	82	81.2	265	86.6
Divorced	1	1.9	12	11.9	12	11.9	25	8.5
Widowed	2	1.9	5	5.0	6	5.9	13	4.3
Level of education								
Illiterate	29	28.2	31	30.7	43	42.6	103	33.8
Primary	51	49.5	51	50.5	50	49.5	152	49.8
Secondary	15	14.6	19	18.8	8	7.9	42	13.2
Tertiary	8	7.7	0	0	0	0	8	2.6
HH size								
<5	30	29.1	34	33.7	32	31.7	96	31.5
5–7	48	46.6	51	50.5	53	52.5	152	49.8
>7	25	24.3	16	15.8	16	15.8	57	18.7
Land holding								
< 0.25 ha	34	33.0	65	64.4	53	52.5	152	49.8
0.25 to 0.5 ha	43	41.8	27	26.7	37	36.6	107	35.1
> 0.5 ha	26	25.2	9	8.9	11	10.9	46	15.1

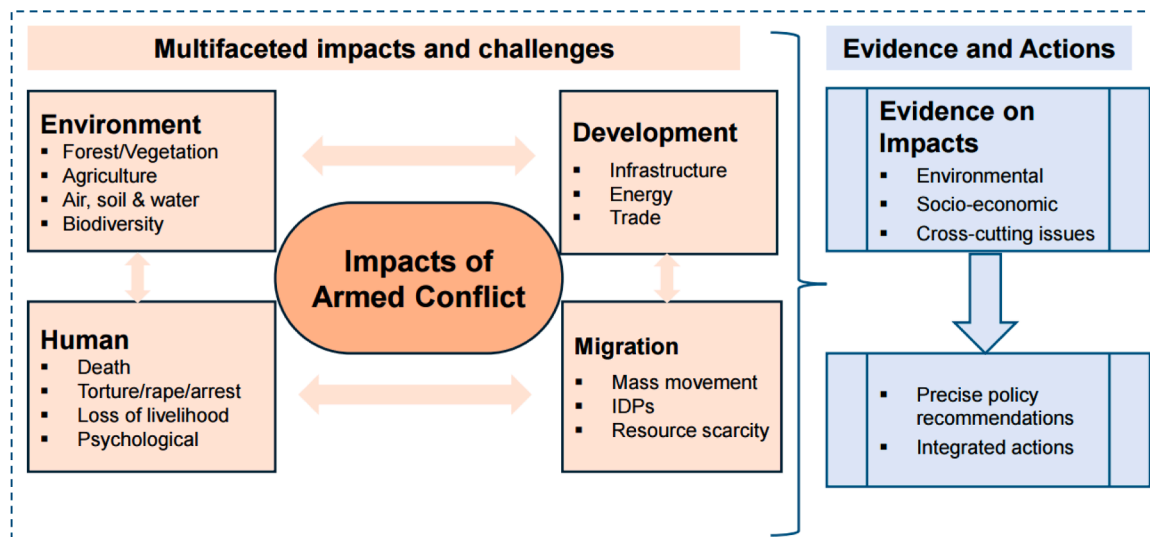


Fig. B1. Conceptual framework of the research illustrating the multifaceted direct and indirect impacts of conflict on the environment and human well-being.



Fig. B2. Farmers plowing farmland using donkeys in Abergelle-Yechila, Tigray, Ethiopia.



Fig. B3. Initiatives to reduce forest dependence through private woodlots cultivation in Atsbi, Tigray, Ethiopia.

Data availability

Data will be made available on request.

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