Science of Remote Sensing 8 (2023) 100108

Contents lists available at ScienceDirect

Science of Remote Sensing

journal homepage: www.sciencedirect.com/journal/science-of-remote-sensing

Remote sensing reveals how armed conflict regressed woody vegetation cover and ecosystem restoration efforts in Tigray (Ethiopia)

Emnet Negash [a,b,*], Emiru Birhane [b,c,d], Aster Gebrekirstos [e], Mewcha Amha Gebremedhin [f,g], Sofie Annys [a], Meley Mekonen Rannestad [d], Daniel Hagos Berhe [h], Amare Sisay [h], Tewodros Alemayehu [i], Tsegai Berhane [j], Belay Manjur Gebru [k], Negasi Solomon [k], Jan Nyssen [a]

[a] *Department of Geography, Ghent University, Ghent, Belgium*
[b] *Institute of Climate and Society, Mekelle University, Mekelle, Ethiopia*
[c] *Department of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia*
[d] *Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway*
[e] *World Agroforestry Center, Nairobi, Kenya*
[f] *Department of Water Resources, University of Twente, Enschede, The Netherlands*
[g] *Institute of Geoinformation and Earth Observation Sciences, Mekelle University, Mekelle, Ethiopia*
[h] *Department of Natural Resources Management, Adigrat University, Adigrat, Ethiopia*
[i] *School of Earth Sciences, Mekelle University, Mekelle, Ethiopia*
[j] *College of Law and Governance, Mekelle University, Mekelle, Ethiopia*
[k] *Tigray Institute of Policy Studies, Mekelle, Ethiopia*

ARTICLE INFO

Keywords:
Desertification
Land restoration
Environmental damage
Earth observation
Vegetatation change
Ecocide
Mass displacement
Tigray war

ABSTRACT

In recent years, armed conflicts are globally on the rise, causing drastic human and environmental harm. The Tigray war in Ethiopia is one of the recent violent conflicts that has abruptly reversed decades of ecosystem restoration efforts. This paper analyzes changes in woody vegetation cover during the period of armed conflict (2020–2022) using remote sensing techniques, supplemented by field testimony and secondary data. Extent of woody vegetation cover was analyzed using Normalized Difference Vegetation Index (NDVI) thresholding method from Sentinel 2 images in Google Earth Engine, and scale of de-electrification was qualitatively analyzed from Black Marble HD nighttime lights dataset, acquired from NASA's Black Marble team. The magnitude, direction as well as the mechanisms of change in woody vegetation cover varied across the region and over time. Tigray's woody vegetation cover fluctuated within 20% of the landmass. Mainly scattered to mountainous areas, the dry Afromontane forest cover declined from about 17% in 2020 to 15% in 2021, and 12% in 2022. About 17% of the overall decline was observed between 500 m and 2000 m elevation, where there is higher anthropogenic pressure. Land restoration practices meant to avert land degradation and desertification were interrupted and the area turned warfare ground. In many areas, forests were burned, the trees cut and the area became barren. The suspension of public services such as electricity for household or industrial use created heavy reliance on firewood and charcoal, further threatening to compound weather and climate. The magnitude of disturbance in a region that is already at a very high risk of desertification requires urgent national and international attention. Continued ecosystem disturbance could eventually make the domain part of a wider desert connecting the Sahel to the Afar Triangle, a scenario which may render the area uninhabitable.

1. Introduction

Over the past century, there have been numerous civil and interstate wars worldwide, some of which are still raging today. Wars typically break out over the distribution of scarce resources like fertile farmland in heavily populated areas (Vučinić et al., 2012). Many of these conflicts have drastic environmental consequences, including biodiversity loss, and increased pressure on various natural resources, such as fish stocks (Chowdhury et al., 2023; CEOBS, 2022; Serhii et al., 2022; Pereira et al., 2022; Mahreen, 2022; Lawrence et al., 2015; Machlis and Hanson,

* Corresponding author. Department of Geography, Ghent University, Ghent, Belgium.
E-mail address: emnet.negash@ugent.be (E. Negash).

https://doi.org/10.1016/j.srs.2023.100108
Received 16 August 2023; Received in revised form 19 October 2023; Accepted 7 November 2023
Available online 11 November 2023

2008). Predicting the precise environmental impact of any battle, however, remains challenging.

Conflict induced environmental impacts can be direct or indirect (Solokha et al., 2023; Zhang et al., 2023; Rawtani et al., 2022; Solomon et al., 2018). Direct environmental impacts include habitat destruction and deforestation to deny hiding places, and damage to fresh water supplies, among others. As compared to the direct impacts, indirect impacts are dozens and often take longer time to account (Reuveny et al., 2010). They include land abandonment and degradation, over use of woody vegetation for firewood or charcoal preparation, loss of wildlife as animals are hunted for bushmeat, land use change degrading agricultural land and vegetation; deterioration of norms in favor of environmental protection, and in many cases war refugees dump waste and damage ecosystems in pursuit of essentials such as food, land, and firewood (Certini et al., 2013; Reuveny et al., 2010).

Sometimes war may have a short-term positive effect on the environment as it reduces ordinary activities that harm the environment. During WWII, a decrease in fishing activity in the Atlantic Ocean and hunting in Norway and Guam resulted in increased fish stocks and wild animal stocks. Similarly, global carbon emissions as well as growth rate of the NO_X emissions from the combustion of fossil fuels declined during WWI and WWII (Reuveny et al., 2010; Houghton and Skole, 1990; Smil, 1990). Moreover, natural resource extraction, waste, and the release of pollutants was reduced during the WWII in Finland (Laakkonen, 2004), and explosives left in the Kuwait desert after the 1991 Gulf War kept hunters and joyriders away, leading to increased vegetation and animal stocks in the area (Reuveny et al., 2010).

However, empirically, most studies on the impacts of armed conflict revealed the negative effect of war on the environment. Wars in Myanmar, Cambodia, Liberia and the Democratic Republic of Congo, the Soviet war in Afghanistan in the 1980s, the US war in Vietnam in the 1960s and 1970s, and the French war in Morocco in the 1920s intensified deforestation (Reuveny et al., 2010; James et al., 2003; Baker et al., 2003). Dikes and dams were destroyed during the war between Japan and China (1937–45), and arable lands were flooded during the Korean War (McNeill, 2001; Biswas, 2000). Recently, the Kakhovka hydroelectric power dam in Ukraine was destroyed unleashing downstream flooding (BBC News, 2023). Similarly, the recent wars in Ethiopia, Ukraine and Syria continue to cause harm to forests and other ecosystem services (Solokha et al., 2023; Daiyoub et al., 2023; Weldegiargis et al., 2023). Reports have it that Ukraine builds a case of ecocide against Russia as dead dolphins wash ashore (Santora, 2023).

Moreover, it is not an uncommon phenomenon for armies to strategically target ecosystem services including agriculture, forest, freshwater and other natural resources during wartime (Ghebreyohannes et al., 2022; Nyssen et al., 2022; Weldegiargis et al., 2023; De Waal, 1991). Both in 20th century wars (e.g., WWII) and in more recent wars (e.g., Syria) natural resources have often been weaponized even though “attacking, destroying, removing or [the] rendering useless [of] objects indispensable to the survival of the civilian population, such as food, provisions, agricultural areas for production of foodstuffs, crops, livestock, supplies and drinking water installations and irrigation works”, is prohibited by Article 54 of the 1977 Protocol of the 1949 Geneva Conventions (ICRC, 1977a; ICRC, 1977b).

In African agrarian societies, there are several examples of the interference of armies in agricultural production during wartime (Nyssen et al., 2022; Macrae and Zwi, 1994). In the Angolan civil war, farmers were not allowed to cultivate their lands without military escorts to protect them from rebels (Carranza and Treakle, 2014; Bowen and Steinberg, 2003). In Sudan and Somalia, both government and rebel armies targeted storage facilities to demotivate the community to re-establish the grain supplies (Macrae and Zwi, 1994). On top of the destruction of crops in South Sudan during the Second Sudanese civil war (Keen, 1991, 1994), the pastoralist communities were impoverished by the confiscation and killing of their livestock. Also, in Somalia during the rule of the military Barre regime (1969–1990), government troops attacked herders at wells and watering points, while additionally poisoning wells and destroying water tankers (Macrae and Zwi, 1994). Also, in garrison towns, blockades of food were often maintained for complex commercial and private (economical) interests (Macrae and Zwi, 1994; Kuol, 2014). In the previous civil war in Tigray (northern Ethiopia) between the central Derg government and the Tigray People's Liberation Front (TPLF) between 1975 and 1991, ground and air offensives by the Ethiopian army were rampant, targeting livestock, croplands, houses and storage facilities with the aim of weakening Tigray's rural economy. This way, the government wanted to make sure that the Tigrayan peasants would not be able to access food or sell their labor (Hendrie, 1994). The intention was, the more people that fled, the lesser the support for TPLF would be – “dry the sea to catch the fish”.

A deadly Ethio-Eritrean war, between 1998 and 2000, resulted in serious habitat changes (Eniang et al., 2007; Solomon et al., 2018). Nevertheless, yet again another devastating war raged between the federal government of Ethiopia and the Tigray regional state from November 2020 to November 2022 (Fiseha, 2023; Burki, 2022; Ibreck and de Waal, 2022). The conflict has resulted in significant humanitarian concerns, including reports of civilian casualties, mass displacement, ethnic cleansing, and allegations of war crimes and crimes against humanity (UNHRC, 2023; HRW, 2022; ARTE, 2022; Associated Press AP, 2022; Vanden Bempt et al., 2021; CNN, 2021). Despite a peace deal signed in November 2022 (Wight, 2022), the humanitarian situation barely improved and crimes against humanity such as ethnic cleansing continued (HRW, 2023). Neither humans and their infrastructure nor the natural environment were spared through the process.

Moreover, the war is feared to have caused drastic ramifications on the ecosystem. Despite claims that the magnitude and character of the environmental damage of the Tigray war may amount to ecocide, there are barely any scientific studies detailing the environmental impacts. Although field-based investigation to the level of damage inflicted on the natural environment is complicated by access and safety issues (Addis Standard, 2023; Aung, 2021), it is possible to examine the environmental changes using advances in earth observation techniques (Solokha et al., 2023; Marzolff et al., 2022; Serhii et al., 2022; Nyssen et al., 2022; Garzón and Valánszki, 2020; Al-doski et al., 2013; Silleos et al., 2006).

Remote sensing is a powerful tool for studying the impact of armed conflict on the environment, especially in areas where access is limited due to conflict (Bennett et al., 2022). Remote sensing data has proven to be particularly helpful for tracking war-related damage and for identifying a wide range of conflict events, from troop movement and the building of new trenches to damaged and destroyed infrastructure, flows of internally displaced populations, and changes in economic activities (Sticher et al., 2023; Avtar et al., 2021; Zwijnenburg and Ballinger, 2023). Remote sensing has augmented environmental impact assessment in conflict scenarios, which has greatly enhanced post-conflict reconstruction (Avtar et al., 2021). Recent studies have used remote sensing to monitor water resources and infrastructure in the Russia-Ukraine conflict (Shumilova et al., 2023), and to track land use/land cover changes due to armed conflict using machine learning (Mhanna et al., 2023; Demissie et al., 2022). Remote sensing is a valuable tool for monitoring the environmental dimensions of armed conflicts and can provide valuable insights into the impact of armed conflict on the environment (Conflict and Environment Observatory CEOBS, 2020). Hence, this study aims to assess changes in woody vegetation cover and the potential mechanisms of change during the Tigray war leveraging the available remote sensing and earth observation techniques.

2. Study area

2.1. Overview of the study area

Although the study area has various names and sizes over time

(Nyssen and Demissie, 2023), Tigray is currently a regional state situated in the northern Ethiopia, between 36° 26′ 45″ E – 39° 59′ 28″ E longitude and 12° 15′ 20″ N – 14° 50’ 44” N latitude (Fig. 1). Bordering Sudan in the west, Amhara region in the south, Afar region in the east and Eritrea in the north, Tigray has a landmass size of 53,000 km^2. The Horn of Africa, especially the Red Sea region has a long history of geopolitical turmoil and social unrest (Plaut and Vaughan, 2023; De Waal, 2015; Plaut, 2013). The strategic geopolitical importance of the Red Sea is among the major triggering factors. The study area found within 50 km distance from the Red Sea has sustained frequent wars causing harm to humans and the environment.

2.2. Tigray’s recent history of land restoration

Tigray is a desertification hotspot (USDA, 1998), encircled by the Sahel desert in the west and northwest and Afar in the east, in which one of the most hostile environments on earth is found. Natural resource restoration was one of the main pillars in the success of Tigray’s development policy intended to avert the risk of desertification and recurrent droughts, ensure food security, and reduce poverty. The main implementation strategies included community mobilization on free and paid labor, with the lion’s share being free labor. Every farmer spends 20–40 days of free labor on natural resource rehabilitation mainly on soil and water conservation in the dry season and tree planting during the rainy season (Gebrekirstos and Birhane, 2023; Negash and Birhane, 2023; CEOBS, 2022; Hagazi et al., 2020). This award-winning conservation-based practice has been implemented for the last three decades (Whiting, 2017; Munro et al., 2019). Local and international partners were also involved in supporting these environmental restoration activities.

The natural resource-based agricultural development policy in Tigray for the last 30 years after the civil war in 1980s has brought the regional landscapes to be greener than it has been known for its barren and dry landscape (Munro et al., 2019; Nyssen et al., 2014) and improved soil health (Gebremeskel et al., 2019). According to Hagazi et al. (2020), Tigray’s woody vegetation cover improved from below 3%–17% in the last three decades. In line with this, Nyssen et al. (2014) investigating conditions of the woody vegetation, soil and water conservation and land management activities over 145 years noted remarkable peak in woody vegetation cover in the 1930s, decline afterwards and then achievement of a second peak in the early 21st century. The restoration process in the region was comprehensive and the outcome was visible in improving the economy through increased ecosystem services and the livelihood of the people in the region (Solomon et al., 2018; Hadgu et al., 2019; Woolf et al., 2018).

The policy has also received international recognition and Tigray was awarded with the UN-backed future policy award in 2017 (Whiting, 2017). These land restoration practices including soil and water conservation works and tree planting activities have been interrupted over the last three years, since 2020. Labor mobilization was not possible in 2020 because of COVID19 pandemic and the latter two years (2021 and 2022) due to the Tigray war. The over three decade’s effort and vision of the community was abruptly disrupted following the breakout of the armed conflict in November 2020. While incidents are not sufficiently communicated, war reverse development, largely destroying the environment, regardless of existing legal mechanisms to prevent damage (Sands et al., 2018; Handl, 2012; Schindler and Toman, 2004; Sohn, 1973).

3. Methods

This study analyzed changes in woody vegetation cover as well as potential mechanisms of these changes over the period of armed conflict (2020–2022) in Tigray (Fig. 1). Recent advances in earth observation techniques and available satellite products were employed, and relevant media reporting as well as field photos were consulted. Sections below present illustrations of the methods and materials used in this study.

3.1. Changes in woody vegetation cover

The Normalized Difference Vegetation Index (NDVI) derived from the multispectral Sentinel 2 satellite imagery was used as a proxy to detect alterations in vegetation cover (e.g. Ardavan et al., 2012; Juszak et al., 2014). This commonly used method describes the discrepancy

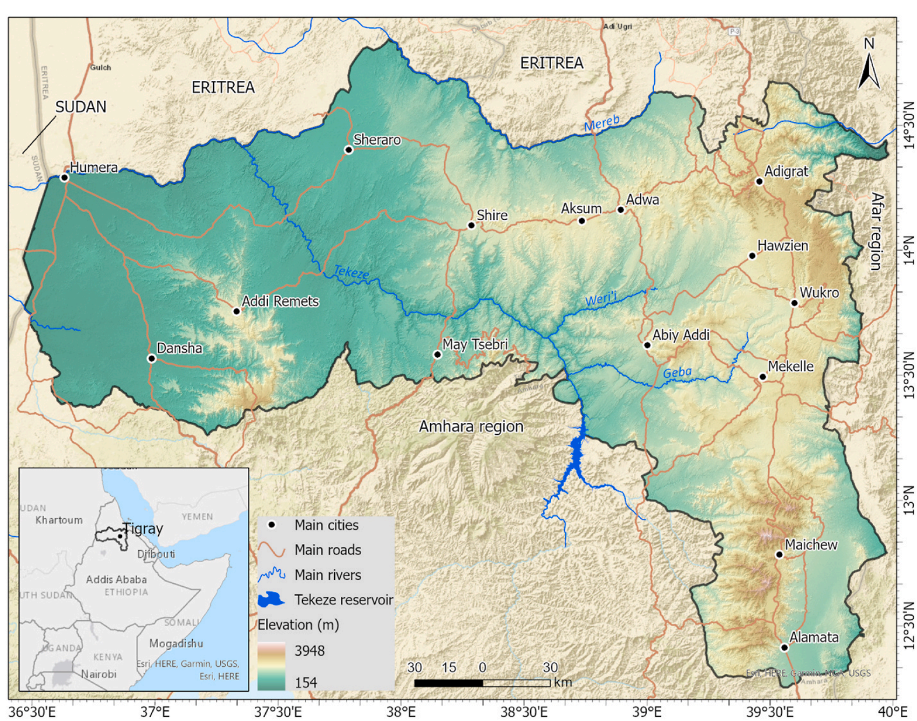

Fig. 1. Location and topographic map of the study area (source: SRTM from USGS, and administrative maps from UNOCHA).

between the amount of near-infrared and red light reflected by vegetation. Photosynthesizing vegetation absorbs red light and reflects near-infrared light, resulting in areas with healthy vegetation having NDVI values close to 1. On the other hand, areas with reduced photosynthetic activity absorb proportionally less red light, and so have lower NDVI value. For the same reason, bare ground tends to reflect red and near-infrared light evenly, and so has NDVI values close to 0. Water has negative NDVI values because it absorbs near-infrared much more than red light.

Median spectral reflectance value of images with less than 3 percent cloud cover, over a period of 3 months between January and March were used to calculate NDVI value of the respective years. Considering the dry months helps in disentangling the effects of rainfall seasonality on vegetation phenological stages and cloud cover. The median spectral reflectance values of the Sentinel images were chosen in order to avoid the influence of extreme values induced by clouds or their shadow (Nyssen, et al., 2022).

NDVI values for the consecutive years were used as a baseline to filter woody vegetation using the NDVI thresholding method (Feng and Fan, 2019) as a breakpoint to detect woody vegetation from lower vegetation. This method limits possible bias from minor changes in greenness or the influence of soil color, among others. Although the dry season is preferred over other months to avoid bias from seasonal vegetation phenological stages, the dry forest, especially deciduous vegetation in the lowlands on the other hand tend to shade their leaves to adapt to the seasonal climate cycle. For this, considering different NDVI thresholds for different agroecology coupled with an onscreen ground truthing seemed reasonable.

3.2. NDVI thresholding method

To detect the best matching woody vegetation threshold, multiple NDVI breakpoint values were tested over elevations with varying vegetation types. An accuracy assessment of these thresholds was then carried out by assigning 300 random points over three 5 km × 5 km grids at various elevation zones: highland (>1500 m), lowland (<1000 m) and the transitional zone (1000–1500 m). Our analysis found that woody vegetation cover is best detected using different thresholds for the different elevation zones (Fig. 2). The highest accuracies have been achieved for threshold values of 0.3 in the highlands (87%), 0.25 in the transitional zone (92%) and 0.2 in the lowland zone (83%), in which evergreen and deciduous vegetation are found at reasonable mix. Hence, these NDVI values have been applied in the respective elevation zone. To further narrow down any possibility of bias from weeds, valley bottom wetlands or irrigated crops with NDVI values above the threshold, other land cover classes including farmlands were filtered out using the ESA land cover classification (Zanaga et al., 2022).

Moreover, by overlaying the woody vegetation maps over the three consecutive years, change matrix categories were developed to visualize the magnitude and direction of change, such as the vegetation loss or gain over the course of armed conflict. Although the woody vegetation cover and change matrix maps were visualized at regional scale, specific scenes in which sharp change in woody vegetation is observed were further verified using high-resolution DigitalGlobe imagery.

About 500 stratified random validation points were scattered throughout the study domain in which the change matrix revealed decline in woody vegetation cover. With the idea to verify changes over the most inhabited midland and highland regions (Gidey et al., 2023; Negash et al., 2020b; Rettberg et al., 2017; Hurni et al., 2005), the validation points were distributed over the elevation classes between 1000 m and 2500 m. To check whether or not there has been a decline in woody vegetation cover, each of these 500 points were tested over DigitalGlobe imagery on Google Earth for the period before and during the period of armed conflict. This way, accuracy of the change assessment could be quantitatively presented based on binary, "yes" or "no" values.

3.3. Rainfall seasonality

In tropical regions such as Tigray where moisture is the limiting factor (Negash et al., 2020a), rainfall availability determines vegetation conditions and phenological stages (Fensham et al., 2005). The hypothesis is that an increase or decrease of the rains throughout the study period might have contributed to changes in woody vegetation cover. Hence, the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) rainfall dataset (Funk et al., 2015) was analyzed and compared over months and years. Based on the long-term rainfall behavior, the greenness analysis was carried out over the dry months between January and March, where rainfall has the lowest influence on vegetation conditions. Rainfall patterns during the analysis years (2020-2021-2022) have been compared to evaluate the level of bias rainfall might have introduced to the vegetation analysis. Moreover, studies such as Hawinkel et al. (2016) and Barbosa & Kumar (2016) revealed a possible time lag of up to 3 months before the impact of more or less rainfall is reflected on vegetation. Hence, rainfall behavior in the study area was also analyzed for the three months preceding the period in which vegetation conditions are examined, i.e., October, November, and December.

3.4. Field testimonies

While field-based investigation remains challenging due to safety and security issues (Addis Standard, 2023), pieces of evidence continue to disseminate through conventional and social media[1] (Gebrekirstos and Birhane, 2023; Negash and Birhane, 2023; ICRC, 2022). Although many of these testimonial sites are localized, depending on available media reporting or presence of personal contact in the area, temporal changes in woody vegetation over these sites were investigated using available time series DigitalGlobe imagery. Needless to mention that image quality and availability are among the challenges further complicating the task (Gorsevski et al., 2012).

3.5. De-electrification and conflict incidents

The Black Marble high definition (HD) nighttime lights showing electrification levels in Tigray's three major cities namely Mekelle, Aksum, and Shire were acquired from the Black Marble team of the National Aeronautics and Space Administration (NASA). These are the same images reported on the BBC World services (Byaruhanga, 2022), highlighting how a war zone faded from space. Monthly average spectral reflectance of these images for the period of September 2020 (pre-war), August 2021 (wartime), September 2021 (wartime), and August 2022 (wartime) were compared and qualitatively evaluated. These Black Marble HD images represent the spatiotemporal dynamism in the (de) electrification between September 2020 and August 2022. Changes in spectral reflectance indicate variability in electrification and thereby determine households' access to power facilities for domestic use, such as baking, cooking, heating, and lighting or industrial uses. Absence of electricity would then infer inhabitants having to use alternative energy sources such as firewood and charcoal for survival.

On the other hand, reported conflict incidents of the Tigray war were derived from an existing work (Annys et al., 2021). These included battles, ambushes, air strikes, drone attacks and shelling in the first 14 months, reported up to December 21, 2021. Unfortunately, conflict incidents dataset for the period after December 2021 was not available. Spatial distribution of incidents was compared with occurrence of changes in vegetation cover qualitatively.

[1] First hand twitter message by an official detailing how a landscape surrounding a battlefield was burned. https://twitter.com/ProfKindeya/status/1392170202301935630?s=20. Accessed on 07.05.2023.

Fig. 2. NDVI thresholds to detect woody vegetation cover at different heights, where different vegetation types are found at various compositions. Best fitting threshold values are highlighted in red based on their performance accuracy indicated in percent. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

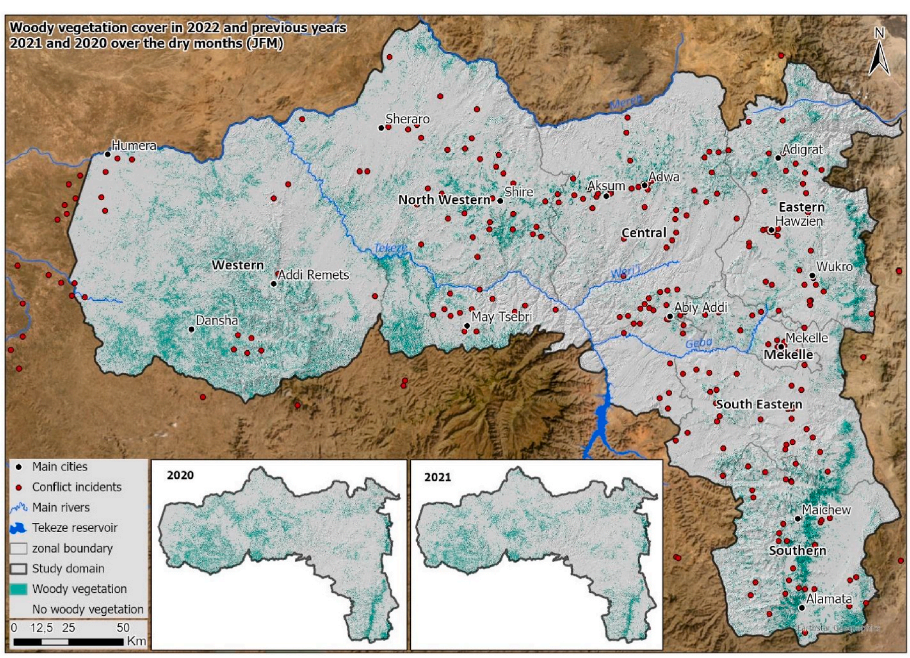

Fig. 3. Woody vegetation before (2020) and during the period of armed conflict (2021, 2022) over the dry months of January, February and March. Conflict incidents for the period between November 2020 and December 2021 (Annys et al., 2021) are overlaid to see their spatial distribution in contrast to landscapes covered with woody vegetation.

4. Results

4.1. Changes in woody vegetation cover during the period of armed conflict

Woody vegetation cover analyzed using the NDVI thresholding method for the dry months between 2020 and 2022 are presented in Fig. 3. In addition to the varying spatial distribution (Fig. 4), Tigray's woody vegetation cover is observed to fluctuate over 20% of Tigray's landmass, with the highest coverage (17%) in 2020, while most of the region's landmass (80%) has no woody vegetation cover beyond scattered remnant trees (Figs. 5 and 6). It is also observed that Tigray's forest cover is mainly localized to the mountain escarpments and less towards lowlands. Nearly 70% of the woody vegetation cover is found above 1500 m elevation (Fig. S1). Geographically, most of Tigray's woody vegetation cover is in the mountain chains along the eastern escarpment between Gira-Kahsu (near Alamata) and Asimba mountains (northeast of Adigrat), along the east-west mountain chains elongated from Asimba to the mountains surrounding Shire, along the Tekeze gorges, and in the highlands of Tselemti-Tsegede-Welkait (Fig. 3).

Although magnitudes of change are varying geographically, Tigray's woody vegetation cover declined from 8889 km^2 (17%) in 2020 to 7777 km^2 (15%) in 2021 and 6574 km^2 (12%) in 2022 (Figs. 3, and Fig. 4). The year 2020 has the highest woody vegetation cover for all elevation categories, except for areas above 2500 m and below 500 m elevation, where a slight increase is seen in 2021 before the decline in 2022. About 17% of the overall decline is found in the lowland and midlands between 500 m and 2000 m elevation.

Locally, western Tigray maintained the highest woody vegetation cover, i.e., 38% of all the vegetation that stayed intact in all three years throughout the region, followed by the northwestern (23%) and southern highlands (16%). On the other hand, the highest decline in woody vegetation cover was also localized to these administrative regions, with about 70% of the overall decline being in western and northwestern zones and 14% in southern Tigray (Figs. 5 and 6).

4.2. Field testimonies

Testimonial sites are localized, depending on available media reporting or availability of personal contact. Most of Tigray's landscapes remain unsafe due to uncleared landmines or continued occupation by hostile foreign and neighboring regional forces. Analytical report by Addis Standard (2023), News24 (2023) and a communication issued by ICRC Ethiopia[2] highlight how explosive remnants of war continued to threaten farming activities, adding a layer to the dire food crisis in Tigray. Although field-based investigation remains challenging due to safety and security issues, presented in Table 1 are some sample illustrative examples demonstrated using media reports and aerial images. Many of these sites assert that Tigray's ecosystem has sustained enormous harm with slight regrowth in some areas.

4.3. De-electrification and the need for alternative energy sources

The Black Marble high definition nighttime lights product obtained from NASA Black Marble team (Román et al., 2019) starkly show the major cities of Mekelle, Aksum, and Shire fading to black over a 25-month period as electricity supplies were effectively shut down (Fig. 7). Electricity, especially in urban areas is the sole source of energy for household and industrial use. Firewood and charcoal become the only resort in its absence. For this, in addition to the alarms that Tigray's regreening efforts had been interrupted and reversed, the CEOBS (2022) report also highlighted that forest areas closer to bigger settlements are at a greater risk due to the increased demand for firewood and charcoal.

For instance, satellite images for an area east of Adigrat called Koma Siwiha show an entire hill, which before the war was green, that was completely deforested in a few months (Fig. S6 and Table 1 [S8]). Widespread disturbance of woody vegetation cover is also evident in the vicinity of Shire (Fig. 8, Fig. S4, and Table 1 [S2–S6]). Moreover, intruders as well as locals striving for survival income are often seen clearing the forest to make charcoal in many corners of the region (Fig. 9). During traditional charcoal making, people dig pits and destroy SWC structures, and the heat destroys the soil biota and structure while the smoke pollutes the air.

4.4. Rainfall seasonality

According to the CHIRPS dataset (Funk et al., 2015), despite slight variability, precipitation depth for all months of the year at all six locations did not show significant difference between 2020 and 2022 (Fig. 10). Summer was slightly higher in 2022 than in 2020 in all locations, except for Humera. On the other hand, 2020 has higher spring rainfall. Fig. S7 also shows that the cumulative rain for the period between January and March varied between 107 mm, mainly in the southern and eastern ends of the study domain, to almost no rain in the western lowlands. Moreover, empirical studies such as Hawinkel et al. (2016) and Barbosa & Kumar (2016) also highlighted up to 3 months lag-time before the impact of higher (lower) rainfall is reflected on vegetation conditions. Hence, rainfall conditions for the months of October to December were also analyzed and found to have no significant difference over the three years (Fig. 10). This indicates the vegetation condition is less likely to have been impacted by the rainfall patterns during the armed conflict period.

4.5. Validating vegetation decline

Results from the systematic quantitative validation showed about 81% accuracy (Table 2). The validation task from DigitalGlobe imagery is challenging due to insufficient images to make the comparison or some of the available images also have bad image quality. Some images do not allow clear display while others are partially or completely covered with clouds.

Moreover, the validation result suggests the possibility to further enhance the classification in a way that better detects spatially varying vegetation behavior, especially the deciduous vegetation in the lowlands. The results have been checked for possible artificial boundaries between elevation categories, above or below 1000 m and 1500 m elevation, that could arise from the NDVI thresholds. During our investigation, thus far, no major artifacts have been detected apart from sometimes the elevation class boundaries exactly fitting the vegetation boundary. Yet, further research towards identifying more suitable breakpoints to better detect spatial vegetation diversity is recommended.

5. Discussion

5.1. Woody vegetation during the period of armed conflict

According to ESA land cover classification (Zanaga et al., 2022), about 30% of Tigray's landmass is covered with either tree cover or shrubland, in other words woody vegetation. While our threshold-based conservative estimates reveal that about 80% of Tigray's landmass has no woody vegetation cover throughout the study period, between 2020 and 2022. Whereas the remaining 20% of the landmass have had fluctuating amounts of woody vegetation cover. Since the analysis period in this paper was limited to the dry season, missing deciduous vegetation throughout the lowlands, and that the model finding for woody vegetation cover were further spatially filtered to the woody vegetation identified by ESA (Zanaga et al., 2022), estimates in this paper are

[2] Twitter message by ICRC Ethiopia: https://twitter.com/ICRCEthiopia/status/1629082523920736258?s=20. Accessed on 05.07.2023.

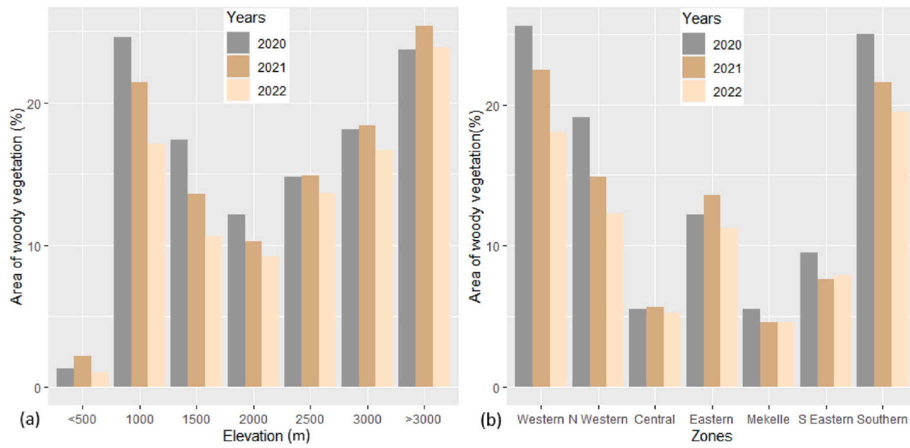

Fig. 4. Proportional area of woody vegetation cover between 2020 and 2022. a) changes in woody vegetation cover along elevation categories, which is the ratio of woody vegetation to area of a particular elevation category, and b) changes in woody vegetation cover along administrative zones.

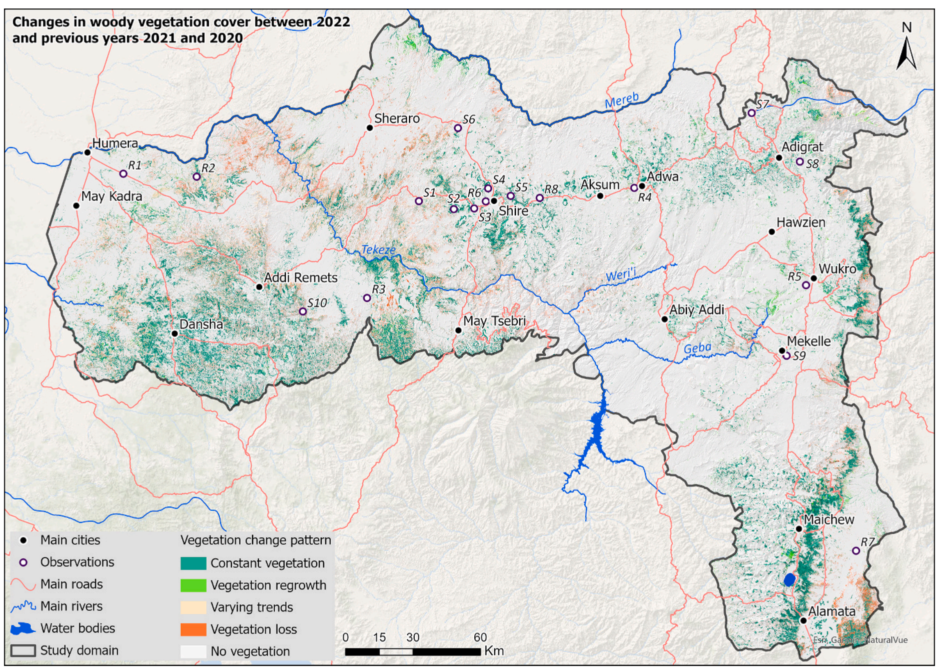

Fig. 5. Simplified map showing changes in woody vegetation cover between 2020 and 2022. Detailed original map on which the analysis is based can be consulted in Fig. S2.

notably conservative.

The 5% loss in vegetation cover during the three-year period agrees with the many pieces of images circulating on conventional or social media (Gebrekirstos and Birhane, 2023; Negash and Birhane, 2023). The highest decline in woody vegetation occurred over the lowlands and midlands between 500 m and 2000 m. The decline over the highlands can be associated with the fact that these elevation categories are known to have higher anthropogenic pressure (Gidey et al., 2023). Hence, the role of human intervention to the decline in woody vegetation cover and the associated ecosystem services (Negash et al., 2020b).

On the other hand, about 70% of the overall decline was localized to western and northwestern zones and 14% in southern Tigray (Figs. 5 and 6).The devastating humanitarian crisis including mass displacement, ethnic cleansing and territorial occupation, especially in western Tigray (HRW, 2022, 2023), destruction of irrigation facilities in southern Tigray (Nyssen et al., 2022), and the enormous concentration of IDPs in northwestern Tigray are explanations. While intruders into Western Tigray caused harm to the vegetation that has economic importance and wildlife in and around Kafta Sheraro National Park (VOA news, 2022), excessive demand for energy sources from native inhabitants and IDPs especially in northwestern Tigray exerted considerable pressure on the woody vegetation cover. Moreover, firewood and charcoal were the only energy alternatives for combatants with enormous numbers staying in the wild for an extended period without having access to modern infrastructure. In addition to the direct environmental damage the combat armors and tanks inflict on the vegetation, trees also make an essential component in constructing bunkers, bridges, or temporary shelters. Although there are no clear estimates on the extent of harm their reliance on woody vegetation might have caused, the areas where combat and combatants have stayed for a longer period would have sustained higher impact.

Moreover, proximity to conflict incidents is often a major determinant of exposure to human or environmental harm. Over three years, between November 2020 and November 2022, Tigray's landscapes sustained hundreds of dreadful conflict incidents scattered throughout the region (Annys et al., 2021, Fig. 11). Warring parties often used heavy

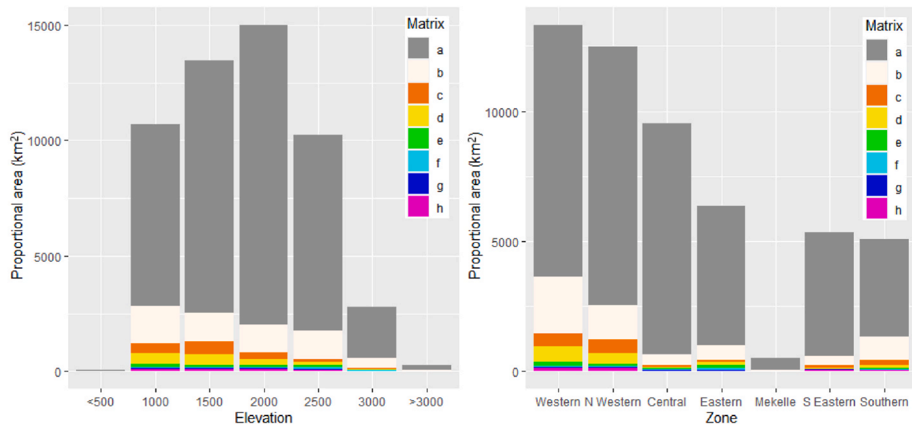

Fig. 6. Proportional areas of woody vegetation change matrix categories over elevation class and administrative zones. a) no woody vegetation in all three years; b) woody vegetation in all three years; c) High in 2020, low in 2021 and 2022 (possible vegetation loss due to war context); d) high in 2020 and 2021, low in 2022 (possible vegetation loss due to war context); e) low in 2020, high in 2021, low in 2022; f) low in 2020, high in 2021 and 2022 (vegetation regrowth); g) only high in 2022 (vegetation regrowth after 2021); and h) high in 2020 and 2022 (possible vegetation loss in 2021 and regrowth in 2022).

artillery and other highly destructive weaponry, not only killing humans and animals, but also destroying vegetation and other natural resources. Whether or not they hit their targets, heavy armaments often destroyed the surrounding ecosystem (Fig. 12; Fig. S3). Among the many pieces of evidence on this account, images circulating on social media and geo-located at "*Hitsats*", a village west of Shire, show at least 225 ha of burned landscape (Fig. S3 and Table 1 [S1]). Another 30 ha of forest is seen burned around Qalamin village in Desa'a forest.

While some wartime damage may have been incidental (Fig. 12), certain actions by the invading forces were clearly targeted to destroy the built as well as natural environment. For instance, according to the Tigray Bureau of Agriculture and Natural Resources, these include the destruction of 237 seedling nurseries and the rendering of many more inoperable to hamper landscape regeneration (Negash and Birhane, 2023). Similarly, De Waal (2021) and Nyssen et al. (2022) revealed how fruit trees in many irrigated lands were destroyed.

According to VOA news (2022), Kafta-Sheraro National Park, the only park for Elephant sanctuary was devastated and Elephants left the park, while many were displaced and killed for their ivory. Frankincense trees and other species of economic importance were disturbed and burned, the park management system and infrastructures were disrupted, and wildlife poached and slaughtered. Moreover, it was reported that armed intruders opened a bush meat restaurant in Adebay, a town at the edge of the park [R1].

Not even sacred land was spared. The forest reserves in and around Waldiba monastery [R3] were exploited after the monks who guarded them were killed or displaced (Abrha, 2022). The satellite-based analysis from Conflict and Environment Observatory (CEOBS, 2022) also revealed that church forests, traditionally considered to be under God's protection and thus off limits for resource extraction (Bongers et al., 2006), were ravaged by intruders from neighboring Amhara and Eritrea, as well as by locals desperate for an income. Episodes like these are likely numbered in the hundreds and spread throughout Tigray, but unfortunately no comprehensive assessment of this type of damage has been done so far.

Even when not explicitly targeted, nature was always a silent victim. For example, because the dry Afromontane forest landscapes characterizing the region were favored both as offensive and defensive positions, many ditches, bunkers, and temporary roads were built there [S7]. This type of preparations and the movements of troops—disregarding the protected status of conservation areas—had a terrible impact on the natural environment and on biodiversity (Fig. 13 and Table 1 [S7]).

Part of the long sustained regular land restoration activities, seedlings planted in June 2020 that were at their early stage of establishment are highly likely to be easily trampled and die by the movement of troops and heavy machinery. Troop movement not only tramples seedlings and saplings, but their enormous number also leaves as much pressure on the forest for building bunkers, bridges as well as cooking their daily meals. In that way, conflict incidents as well as military movement are feared to have had considerable damage on the natural environment. This is happening in a degraded dry Afromontane forest where researchers argue, "the recruitment credit cannot compensate for extinction debt" (Hishe et al., 2022).

5.2. De-electrification and siege: a drastic turnout

A medieval-like siege including de-electrification made a terrific characterization of the Tigray war. As can be seen from Fig. For the better part of the war, Tigray's population has been denied access to essential public services, including to the national electricity grid (Burki, 2022; Byaruhanga, 2022; Abay et al., 2022; Annys et al., 2021). The substitute power supply from the Tekeze dam, the only hydroelectric power source in the region, was not only insufficient but also was damaged by aerial bombardments (Byaruhanga, 2022). Since it was not possible to import spare parts to repair it, access to electricity in Tigray went from bad to worse. Even before destruction, the operation and management of the dam depended on who controlled the dam.

In the absence of the national electricity grid, people heavily relied on natural resources including the remnant natural forests, to sustain themselves. This is especially alarming in towns and cities hosting an overwhelming population of internally displaced persons. The city of Shire in northwestern Tigray received up to seven times its prewar population in which the humanitarian situation was persistently reported to have been grave (Annys et al., 2021). Similarly, IMO (2021) household survey revealed over 39% of all IDPs destined in Shire. In the absence of means to prepare food or heating it becomes obvious that residents including the IDPs would reconsider using the unhealthy firewood and charcoal, which comes from the surrounding forest. A rare video footage[3] by the International Committee of the Red Cross from the same spot shows a line of women carrying firewood from the field, which is a testament to the extensive pressure on forests. Images on Fig. 8 and Fig. S4 also reveal striking evidence of forest disturbance in Shire's surroundings. Fuel wood-based pity trade has now become a widespread practice (Fig. 9).

[3] International Committee of the Red Cross (ICRC). (2022). Ethiopia: rare footage from Tigray Shows health crisis. https://www.icrcnewsroom.org/preview/en/2045/ethiopia-rare-footage-from-tigray-shows-health-crisis/2924. Accessed on 05.07.2023.

Table 1
Sample sites spontaneously illustrated throughout the paper. S1–S9 are sites in which observations are made based on satellite images, whereas R1-R8 are incidents learned from media reporting. See also associated figures.

No.	Location	Lat	Lon	Observations
S1	Hitsats	14.101	37.977	Clear signs of burning can be seen in the surroundings of Hitsats refugee camp. The damage was first spotted from images circulating on social media account of an official[a], and geolocated to the landscape surrounding Hitsats refugee camp west of Shire. Assessment show at least 225 ha burned during fighting in late 2020. Also see Fig. S3.
S2	Asgede	14.070	38.121	Located within 15 km west of Shire, extensive disturbance is seen throughout 2020 and 2022.
S3	Tahtay Koraro	14.073	38.205	Found within 7 km west of Shire, the area experienced continuous clearance of its forest cover throughout 2020 and 2022.
S4	Tahtay Koraro	14.154	38.262	Found within 3 km north of Shire, this part of Hirmi forest is found to have faced excessive pressure throughout 2020 and 2022.
S5	Tahtay Koraro	14.124	38.355	Located 5 km east of shire, another incident of continuous forest clearance is seen.
S6	Seyemti Adyabo	14.396	38.137	Clear signs of forest clearance are present throughout the study period, with slight regreening in 2022. The incident is remarkable like observations on S2–S5. Note that Shire hosted additional +698% IDPs on top of its native inhabitants (Annys et al., 2021). See Fig. 8 and Fig. S4.
S7	Zalambesa	14.458	39.349	Widespread presence of trenches on the farmlands as well as hills partly covered with woody vegetation. Ecosystem disturbance is clearly seen, especially in areas where bunkers are constructed, diverting the natural drainage system. See Fig. 13.
S8	Koma Siwiha	14.262	39.547	A hill covered with forest in October 2020 is half empty in December 2020 and cleared in April 2020 (CEOBS, 2022; Negash and Birhane, 2023). Afterwards slight regrowth is seen after 2022. See Fig. S5.
S9	Mekelle	13.481	39.491	A pile of crop harvest ready for threshing burned by a drone attack near Mekelle University Main campus in late October 2021.[b] See Fig. 12. Nearby vegetation is burned and destroyed
S10	Welkait	13.655	37.502	Widespread forest disturbance including clear signs of burning are seen throughout the hilly escarpment of Tsegede and Welkait, potentially due to agricultural expansion. More extensive forest disturbance is seen around 13.428, 37.536. See also Fig. S6.
R1	Adebay	14.203	36.759	Armed groups from neighboring Amhara operate a bush meat restaurant in Adebay, a town located at the edge of the Kafta Sheraro National Park.[c]
R2	Kafta Sheraro National Park	14.194	37.061	According to VOA news[d], the park was disturbed, many elephants were displaced and killed for their ivory, and wildlife was poached. Elephant tusk (Ivory) is a common commodity being smuggled from the area
R3	Waldiba	13.711	37.766	According to Abay et al. (2022) and Negash and Birhane (2023), forest reserves in and around Waldiba monastery were exploited after the monks who guarded them were killed or displaced.
R4	Almeda Textile	14.157	38.865	Almeda Textile Factory in Adwa is seen largely burned down, possibly leaking chemicals into the environment. Note that the power plant of the factory is situated next to a wetland.
R5	Sheba Leather	13.765	39.572	Sheba Leather Factory in Wukro was shelled, possibly leaking chemicals to the environment.
R6	Shire	14.100	38.281	Rare video footage released by the International Committee of the Red Cross shows a long line of women carrying firewood from the field (ICRC, 2022), which is a testament to the extensive pressure on forests.
R7	Mekhoni	12.696	39.774	According to Nyssen et al. (2022), a large area of irrigation farms in which fruit trees are grown were damaged and the irrigation infrastructure destroyed.
R8	Selekleka	14.116	38.475	According to BBC News, a flood incident on June 26, 2022 claimed lives of at least ten inhabitants and many more people were injured, and settlements inundated in Selekleka.[e]

[a] First hand twitter message by an official detailing how a landscape surrounding a battlefield was burned. https://twitter.com/ProfKindeya/status/1392170202301935630?s=20. Accessed on May 07, 2023.

[b] Twitter post highlighting burning of harvest piles. https://twitter.com/emnet_negash/status/1451513059718144004?s=20. Accessed on July 05, 2023.

[c] VOA news Amharic detailing the level of damage Kafta Sheraro National park has sustained. የቃፍታ ሽራሮ ብሔራዊ ፓርክ ከፍተኛ ጉዳት እንደደረሰበት ተገለፀ. https://amharic.voanews.com/a/6697911.html. Accessed on July 05, 2022.

[d] VOA news Amharic detailing the level of damage Kafta Sheraro National park has sustained. የቃፍታ ሽራሮ ብሔራዊ ፓርክ ከፍተኛ ጉዳት እንደደረሰበት ተገለፀ. https://amharic.voanews.com/a/6697911.html. Accessed on July 05, 2022.

[e] BBC News (2022). Search on for Tigray flood victims as 10 buried. Jul 6, 2022. https://www.bbc.com/news/live/world-africa-61754474?ns_mchannel=social&ns_source=twitter&ns_campaign=bbc_live&ns_linkname=62c54e47c5f5c122c9fc1d2d%26Search%20on%20for%20Tigray%20flood%20victims%20as%2010%20buried%262022-07-06T14%3A15%3A11%2B00%3A00&ns_fee=0&pinned_post_locator=urn:asset:33cadc29-39e6-4edd-b3a4-b-d31ad59bf-ba&pinned_post_asset_id=62c54e47c5f5c122c9fc1d2d&pinned_post_type=-share. Accessed on July 09, 2023.

Moreover, even if the multilayer blockade forced people to rely on firewood and charcoal, an unknown number of bombs that have been planted in many of the forests sometimes make areas inaccessible. However, this creates additional pressure on the forest in areas where they are believed to be safe. A society that has been awarded for its success in land restoration is now forced to take part in reversing their past achievements as they deforest for firewood and charcoal for domestic use or generate survival income.

Furthermore, although little attention is given, women and girls are exposed to heavy workload in the collection and transport of firewood. Smoke-based health problems are also becoming prevalent among the women who take the burden of household care. In addition, consuming half-cooked or raw food becomes increasingly a common practice to save firewood, which could also contribute to the worsening health crisis.

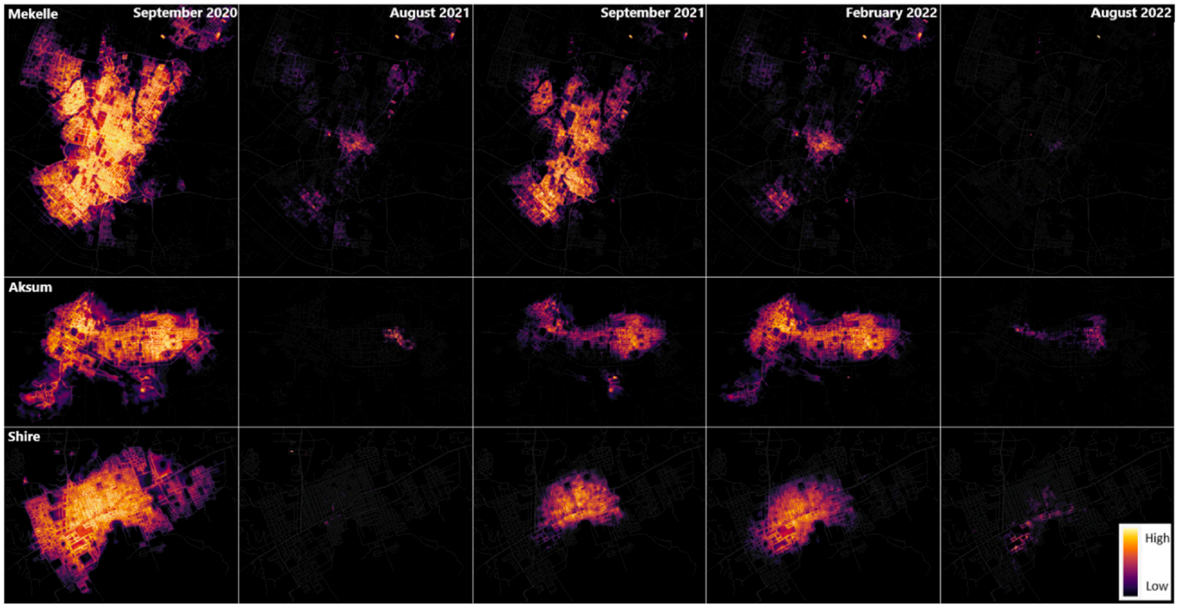

Fig. 7. Electricity in Tigray's three major cities seen fading to black on NASA Black Marble HD nighttime lights. Slight attempts of re-electrification can be seen in late 2021, but are not anywhere close to pre-war conditions.

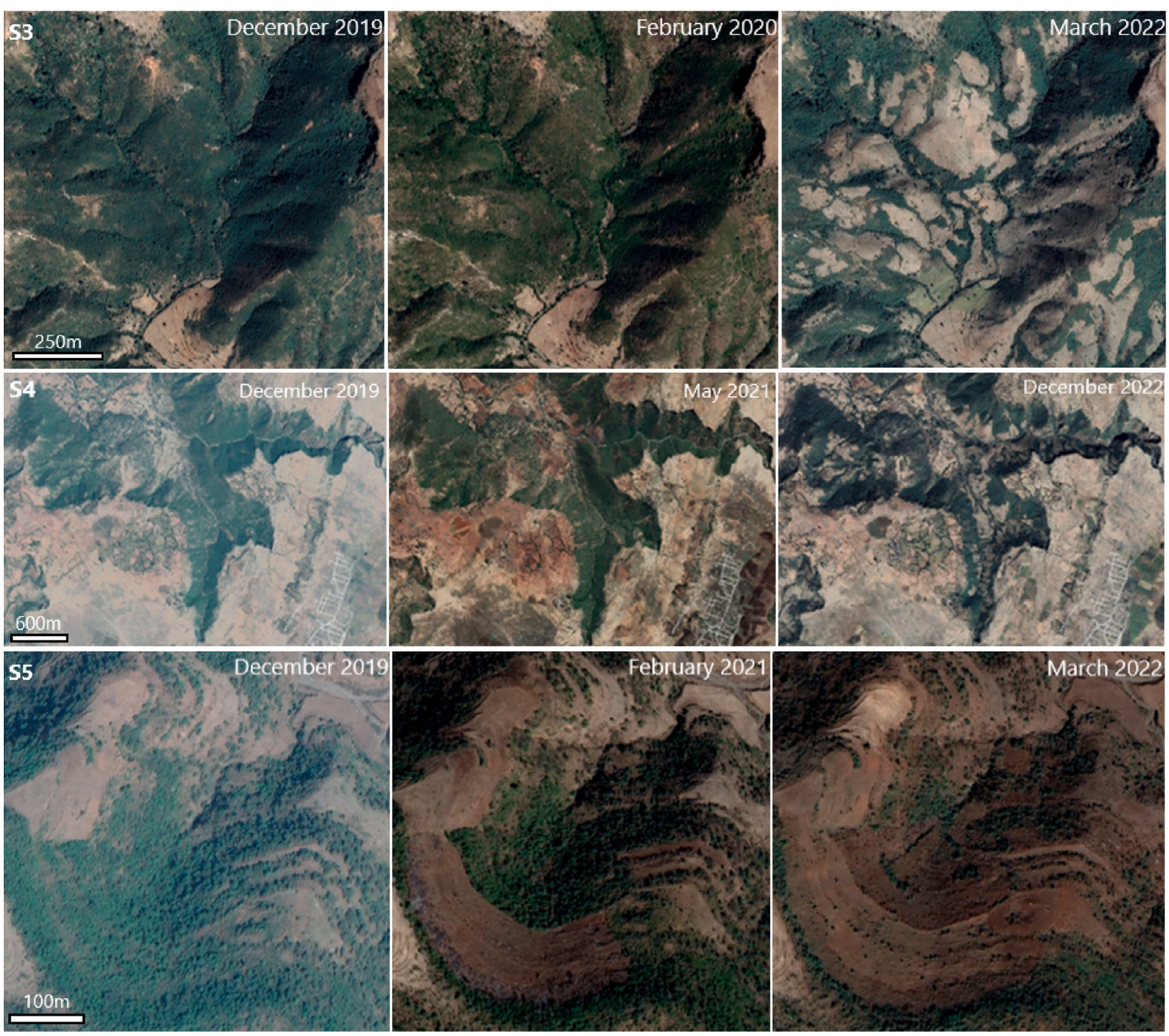

Fig. 8. Testimonial sites around Shire, where woody vegetation has been continuously cleared likely due to the overpopulation exacerbated by enormous internally displaced persons (IDPs) from western Tigray. See also Fig. S4 for additional images, Table 1 [S2–S6] and their locations on Fig. 5.

Fig. 9. Fresh wood prepared for charcoaling in Adyabo (a) and Negash (b) areas, multiple sacks of charcoal prepared for shipping in Negash (c), and multiple heaps of eucalyptus tree cleared in Atsbi (d). These areas are near major protected forest areas and big cities. Charred soil in pictures 'a-c' indicates the area has previously been used for the same purpose at least once. Photos were taken in June 2023 by Goyteom Gebreeziabher (SLMP staff at Tigray Bureau of Agriculture and Natural Resources).

5.3. Ecosystem services disrupted

The war disrupted the ecosystem and the services that humans could get from the environment. A good example of this is the time when the war was launched. The war started towards the end of the rainy season, by the time farmers prepared to harvest their produce. However, about 90% of the harvest from that season was either devastated by locusts, destroyed and burned over many of the hundreds of conflict incidents, left on the field or looted in the 2020 harvest season (FAO, 2021), which coupled with the siege lead to a staggering human suffering including man-made famine (Weldegiargis et al., 2023; BBC News Africa, 2022). Ngussie and Hailu (2023) also reveal how the Tigray war put honeybees in peril. In line with these, an extensive legal analysis by the Allard K. Lowenstien International Human Rights Clinic finds Ethiopia and allies responsible for mass starvation in Tigray (Yale Law School, 2023).

During this time of the year, transhumance, i.e., keeping livestock from many highland households together in the lowlands, is a customary practice in many parts of Tigray, especially in the northwestern, western and southern zones. This created comfortable conditions to loot the livestock concentrated in one place (Negash and Birhane, 2023). Ethiopian and Eritrean forces widely engaged in looting, slaughtering and killing of livestock in these lowlands, which was often witnessed in other parts of Tigray too (Nyssen et al., 2022). It was also not possible to collect animal feed that would have been used for the rest of the dry season.

Farming households who lost their essential means of living during this season were left with nothing but to exchange their belongings or the trees around them for food. On many occasions people eat tree leaves and branches (Nyssen, 2021). Contrary, Ethiopia announced its plans to export food grain (The Reporter, 2022). This is not an exception, rather a continuation of its striking move sending seedlings to neighboring states under its green legacy initiative (Ethiopian Monitor, 2021), while Tigray in Ethiopia continues to endure environmental damage. Tigray's painful experience, among others, shows that mounting international demands (Stop Ecocide Foundation, 2021; Yeo, 2020; Higgins, 2015; Falk, 1989) to make mass destruction of ecosystems punishable necessitate meaningful support (Santora, 2023; Fleming, 2021; NPR, 2021).

5.4. Long-term impacts of ecosystem disturbances

5.4.1. Freshwater ecosystem

Water resources are an integral part of the watershed ecosystem that is also impacted by the war. The conflict-driven degradation of the catchment affects directly and indirectly the quality and quantity of the water resources. Several studies (e.g; Ouyang et al., 2019; Springgay et al., 2019; Mapulanga and Naito, 2019; Sun et al., 2017; Ilstedt et al., 2016) suggested that forest cover increases water infiltration and improves the availability of groundwater source and thus maintains healthy ecosystems. Ilstedt et al. (2016) further demonstrated that moderate tree cover on degraded lands result in increased infiltration ranging from 1.6 to 9 times more highlighting that forest cover plays an important role in improving groundwater resources in dry tropics. In the past 30 years, large-scale mass mobilization efforts in environmental conservation and rehabilitation have greatly contributed to increasing groundwater recharge and water level in the region (Gebregziabher et al., 2016).

In addition, water pollution from the use of weaponry and leak of toxic substances from industrial and other facilities remain major concerns. During the war, industrial facilities were particularly targeted by military operations and hazardous chemicals from these facilities are feared to have leaked into the environment [R4-R5]. Unfortunately, it will take years for the ecosystem to recover, and thus freshwater resources will continue to be depleted.

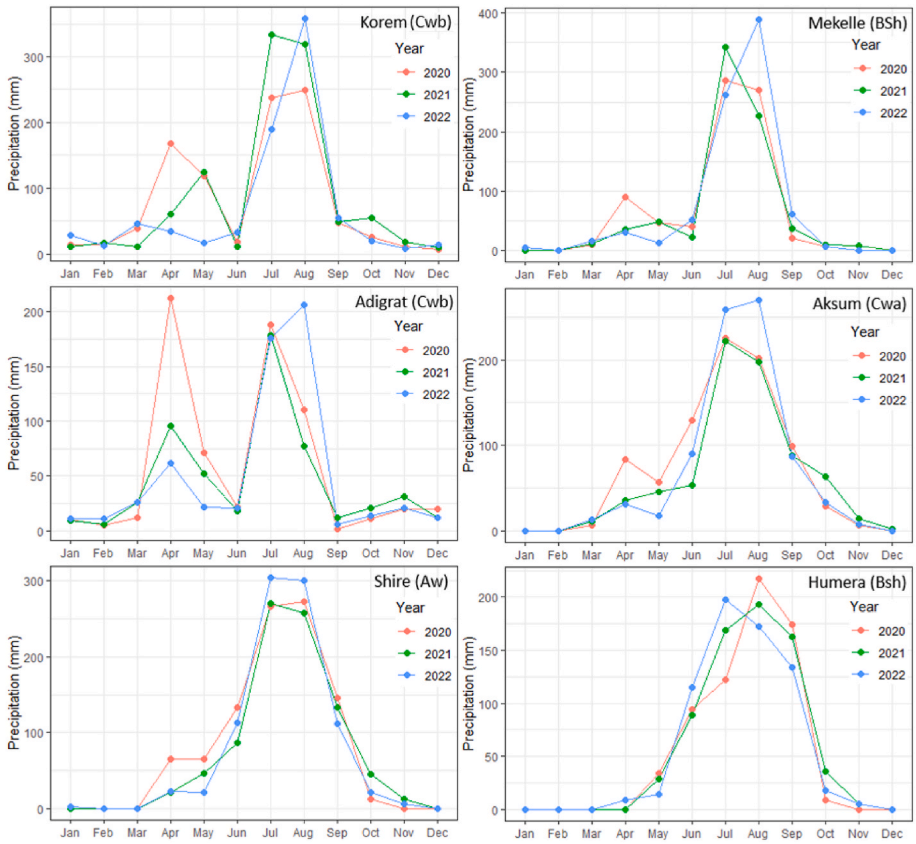

Fig. 10. Long-term average monthly rainfall distribution, as derived from the Climate Hazards Group InfraRed Precipitation with Station CHIRPS 2.0 dataset (Funk et al., 2015), comparing 2020, 2021 and 2022 over contrasting regions, with corresponding climate type based on the Köppen classification.

Table 2
Validation results based on 500 stratified random points. Sample points were assigned a binary "1" and "0" labels to confirm or reject decline in woody vegetation cover.

Labels	Count	Percent
Observed decline ('1')	406	81.20
Commission error ('0')	94	18.80
Predicted decline	500	100.00

5.4.2. *Weather and climate*

The dry Afromontane forest, along the eastern escarpment including Desaa are rich in Juniperus and Olea trees as well as *Erica arborea*; it is often known as a fog forest since it mainly receives moisture from the clouds (Teferi, 2021). The first two species are the cloud and climax species, longer in height and evergreen. The physiognomy of the two species increases the capacity of the forest to intercept moisture and serve as a windbreak to the warm air and dust blowing from the Afar-Triangle. However, the continued disturbance of the forest along this escarpment could contribute negatively to the long-term ability of the forest to buffer and receive moisture from the clouds, modifying weather and climate of the region.

The effects of large-scale destruction of natural resources are likely to impact atmospheric conditions in the region. Although the long-term impacts on the climate system are yet to be seen, a few outcomes have already become apparent. The damage to conservation structures and the cutting of trees resulted in flooding in many watersheds, cities and towns. Unable to cope due to the devastation inflicted on sewage systems, several such episodes ended with loss of human life. In fact, even though rainfall levels were not any different from previous years, the towns of Selekleka, Adigudom, and Maichew faced destructive flash floods that would otherwise have been easily controlled. At least ten inhabitants were killed and many more injured in Selekleka on June 26, 2022 (BBC News, 2022).

To summarize, the Tigray has seen several direct and indirect mechanisms of environmental harm during the period of armed conflict (Fig. 14). Among the direct mechanisms include warfare and troop movement. Vegetation and crops were burned, wildlife caught on crossfire, saplings trampled, and cutting of trees for bunker construction during the period of armed conflict. Local and invading armed forces, in their hundreds of thousands, who lived on wild temporary shelters for an extended period also caused direct environmental harm as firewood and charcoal were the primary means of cooking. On the other hand, among the multiple indirect, perhaps even more important mechanism of ecosystem disturbance include the overpopulated cities due to large scale displacement and ethnic cleansing, especially from Western Tigray. Over 2 million IDPs were left to live helplessly without basic income, hygiene or cooking facilities. Other indirect mechanisms include suspension of the power grid forcing residents resort to firewood and charcoal, state collapse leading to interruption of the longstanding ecosystem restoration efforts, lack of living income making youth and farmers to reconsider trees as means of earning, and territorial annexation in which trees and wildlife were endangered. Altogether, these incidents created a condition in which the environment became a silent victim facing multipronged threats, which unless reversed will have further compounding effect exacerbating lives and livelihoods.

5.5. *Limitations and future research*

Due to safety and security issues, this study relied on remote sensing techniques. A follow-up study with a field-based assessment disaggregated by biome type would enhance our understanding of the level of environmental disturbance. We also note that the conflict largely

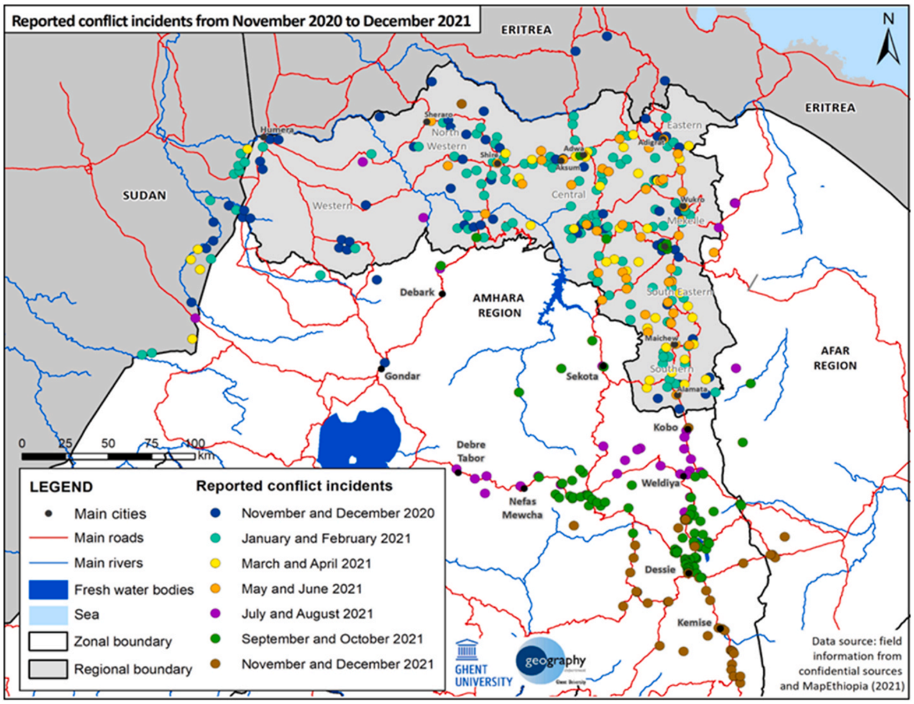

Fig. 11. Reported conflict incidents between November 2020 and December 2021 (Annys et al., 2021).

Fig. 12. Harvest piles ready for threshing burned by a drone strike near Mekelle University Main campus in October 2021. At the time, besieged farming households had nothing but counting on these produce.

disrupted the ecosystem service values that humans could benefit from, which we have not addressed in sufficient detail. Further research involving economic valuation of the induced changes in various ecosystem service categories and functions (Berihun et al., 2021; Negash et al., 2020b; Costanza et al., 2014) would also be extremely valuable.

6. Conclusion

Results obtained from earth observation reveal that the Tigray sustained drastic ecosystem disturbance during the armed conflict. Mainly scattered to mountainous areas, Tigray's dry Afromontane vegetation was widely disturbed. Notably, the armed conflict interrupted and reversed the long-sustained ecosystem restoration efforts that were meant to avert land degradation and desertification. The lengthy siege which included suspension of essential services such as electricity for household or industrial use created a heavy reliance on natural resources such as firewood and charcoal. This was especially intense in areas where there is higher concentration of IDPs, such as in north-western Tigray.

On the other hand, western and southern Tigray, where evidence of ethnic cleansing and land annexation is mounting, remain hotspots in which the forest and wildlife are threatened. Although the long-term climatic impacts are yet to be observed, troop movement, construction of trenches, warfare and other military activities are already seen compounding the impacts of extreme weather events such as flooding. Unfortunately, as is the case with the even more drastic humanitarian crisis, environmental harm of the Tigray war remains neglected. Unless the damage is reversed soon, these ramifications will get worse by the day. If time is wasted and there is a continuation of the ongoing ecosystem damage, Tigray could become part of a wider desert connecting the Sahel to the Afar Triangle. In such a scenario, the ecosystem would eventually become uninhabitable and force residents to migrate.

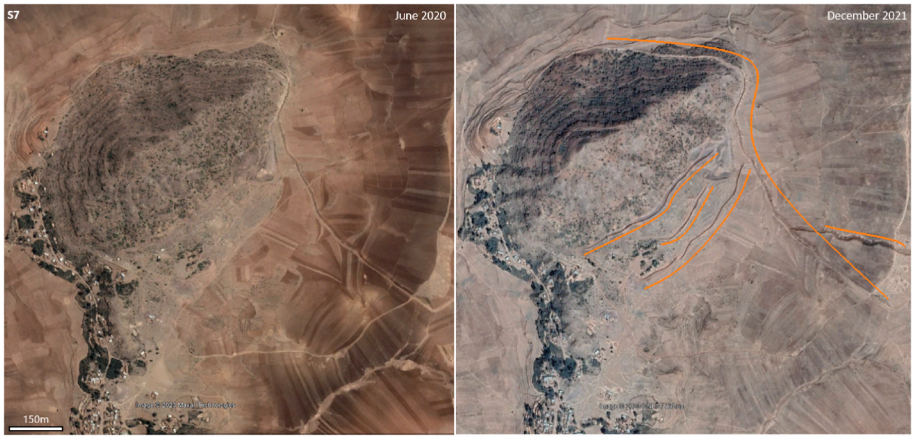

Fig. 13. New trenches are seen on the farmlands as well as hills near Zalambesa. There are clear signs of trenches construction in December 2021 in an area that was partly covered with woody vegetation in June 2020. Similar activities exist on the hilly slopes to the east of this spot as presented in Table 1 [S7].

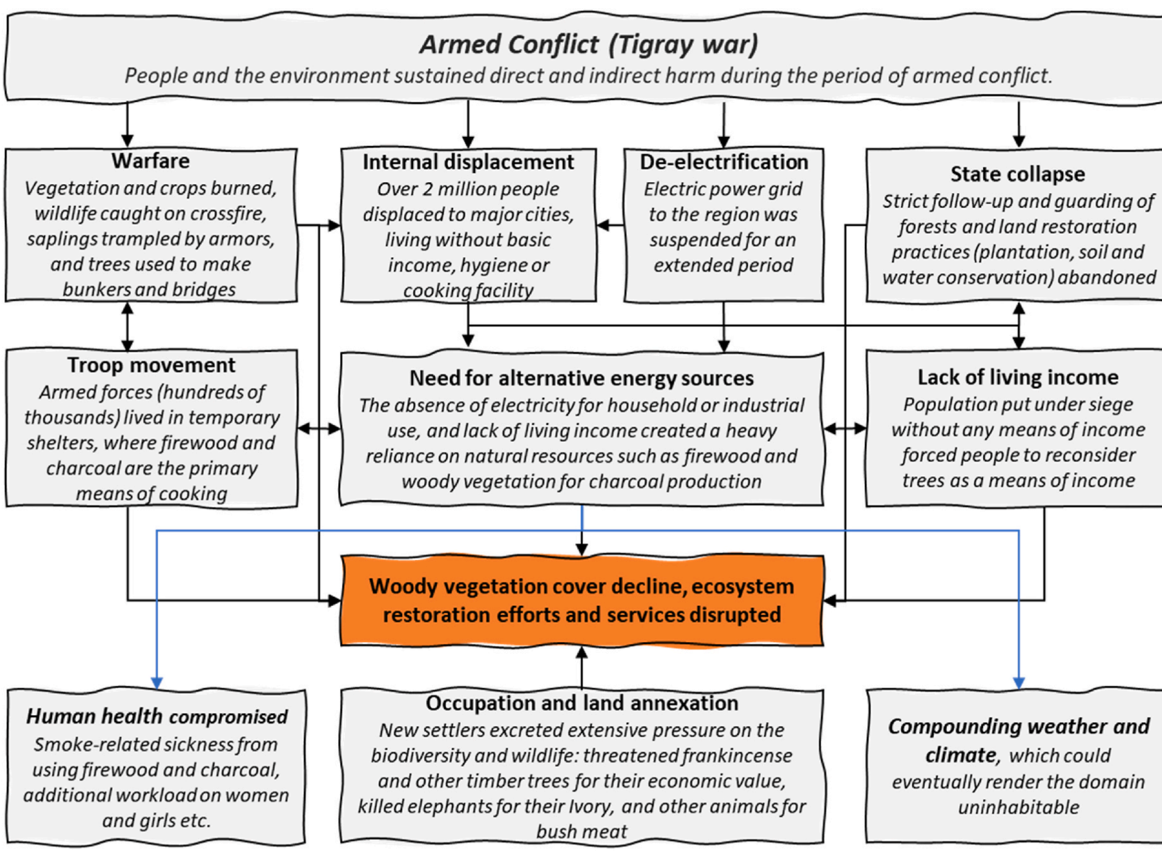

Fig. 14. A diagram summarizing how armed conflict directly and indirectly threatened woody vegetation cover and ecosystem restoration efforts.

The growing number of armed conflicts along with their environmental ramification in recent years, globally, highlights the need for regional and international environmental laws and their enforcement. Similarly, Tigray's painful experience shows that the mounting international demands to make mass destruction of ecosystems punishable necessitate meaningful support. Such a decision by the International Criminal Court would make actors responsible for funding, permitting, or causing severe environmental harm subject to criminal prosecution, hopefully preventing its repetition in the same spot or elsewhere globally. Moreover, coordinated national and international efforts to prevent further destruction and support post-war ecosystem reconstruction are essential.

Funding information

The first author benefited from Ghent University's Special Research Fund – Bijzonder Onderzoeksfonds (BOF) – grant number 01W00420.

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.

Data availability

Data will be made available on request.

Acknowledgements

Authors are grateful to many anonymous persons for the exchange of thoughts, and Goyteom Gebregziabher (SLMP staff at Tigray's Bureau of Agriculture) for sharing field information and photos. The NASA's Black Marble team are also acknowledged for providing the Black Marble HD nighttime lights dataset. We acknowledge the IIE Scholar Rescue Fund, and NORGLOBAL 2 project [grant number: 303600] for supporting Emiru Birhane's research stay at the Norwegian University of Life Sciences. Editors and three anonymous reviewers are also acknowledged for their invaluable efforts to enrich the earlier version of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.srs.2023.100108.

References

Abay, K.A., Abay, M.H., Berhane, G., Chamberlin, J., Croke, K., Tafere, K., 2022. Access to health services, food, and water during an active conflict: evidence from Ethiopia. PLOS Glob Public Health 2 (11), e0001015. https://doi.org/10.1371/journal.pgph.0001015.

Abrha, H., 2022. Targeting Tigray's Heritage and Values. *Eritrea Hub*. https://eritreahub.org/first-comprehensive-analysis-of-the-looting-of-tigrays-heritage-as-ebay-halts-sale-of-ethiopian-treasures#_ftn1. (Accessed 29 June 2023).

Addis Standard, 2023. In: Analysis: Explosive Remnants of War Threaten Farming Activities, Add Layer to Dire Food Crisis in Tigray Region. https://addisstandard.com/analysis-explosive-remnants-of-war-threatens-farming-activities-adds-layer-to-dire-food-crisis-in-tigray-region/. (Accessed 29 June 2023).

Al-doski, J., Mansor, S.B., Shafri, H.Z.M., 2013. War impacts studies using remote sensing. IOSR J. Appl. Geol. Geophys. 1 (2), 11–15.

Annys, S., Vanden Bempt, T., Negash, E., De Sloover, L., Ghekiere, R., Haegeman, K., Temmerman, D., Nyssen, J., 2021. In: Tigray: Atlas of the Humanitarian Situation. https://doi.org/10.5281/zenodo.5804284. Version 2.2. Ghent (Belgium): Ghent University, Department of Geography.

Ardavan, G., Amir, M., Abazar, E., 2012. Utility of the Normalised Difference Vegetation Index (NDVI) for Land/canopy Cover Mapping in Khalkhal County (Iran).

ARTE, 2022. Ethiopia: Tigray Humanitarian Crisis. ARTE Reportage. https://www.arte.tv/en/videos/109207-000-A/arte-reportage/.

Associated Press (AP), 2022. In: Official Document Describes Scale of Abuses in Ethiopia War. https://apnews.com/article/ethiopia-africa-kenya-0cd14684679c605f4c31effe71e0a0ea (Accessed 13 July 2023).

Aung, T.S., 2021. Satellite analysis of the environmental impacts of armed-conflict in Rakhine, Myanmar. Sci. Total Environ. 781, 1–15. https://doi.org/10.1016/j.scitotenv.2021.146758.

Avtar, R., Kouser, A., Kumar, A., Singh, D., Misra, P., Gupta, A., et al., 2021. Remote sensing for international peace and security: its role and implications. Rem. Sens. 13 (3), 439. https://doi.org/10.3390/rs13030439.

Baker, M., Clausen, R., Kanaan, R., N'Goma, M., Roule, T., Thomson, J., 2003. Conflict Timber: Dimensions of the Problem in Asia and Africa, Volume III, African Cases.

Barbosa, H.A., Kumar, T.L., 2016. Influence of rainfall variability on the vegetation dynamics over Northeastern Brazil. J. Arid Environ. 124, 377–387. https://doi.org/10.1016/j.jaridenv.2015.08.015.

BBC News, 2022, 6 Jul 2022. In: Search on for Tigray Flood Victims as 10 Buried. www.bbc.com/news/live/world-africa-61754474?ns_mchannel=social&ns_source=twitter&ns_campaign=bbc_live&ns_linkname=62c54e47c5f5c122c9fc1d2d%26Search%20on%20for%20Tigray%20flood%20victims%20as%2010%20buried%262022-07-06T14%3A15%3A11%2B00%3A00&ns_fee=0&pinned_post_locator=urn:asset:33cadc29-39e6-4edd-b3a4-bd31ad59bfba&pinned_post_asset_id=62c54e47c5f5c122c9fc1d2d&pinned_post_type=share.

BBC News, 2023. Ukraine Dam: what We Know about Nova Kakhovka Incident. https://www.bbc.com/news/world-europe-65818705.

BBC News Africa, 2022. Tigray under Siege - BBC Africa Eye Documentary. https://www.youtube.com/watch?v=1ioOLj_PMwg. (Accessed 7 July 2023).

Bennett, M.M., Van Den Hoek, J., Zhao, B., Prishchepov, A.V., 2022. Improving satellite monitoring of armed conflicts. Earth's Future 10 (9), e2022EF002904. https://doi.org/10.1029/2022EF002904.

Berihun, M.L., Tsunekawa, A., Haregeweyn, N., Tsubo, M., Fenta, A.A., 2021. Changes in ecosystem service values strongly influenced by human activities in contrasting agro-ecological environments. Ecological Processes 10 (1), 52. https://doi.org/10.1186/s13717-021-00325-1.

Biswas, A.K., 2000. Scientific assessment of the long-term environmental consequences of war. The environmental consequences of war: Legal, economic, and scientific perspectives 303, 315.

Bongers, F.J.J.M., Wassie, A., Sterck, F.J., Bekele, T., Teketay, D., 2006. Ecological restoration and church forests in northern Ethiopia. Journal of the Drylands 1 (1), 35–44.

Bowen, N., Steinberg, D., 2003. Food security challenges in post-conflict Angola. Pretoria, South Africa, Institut Français d'Afrique du Sud. 3. In: Drimie, S., Lafon, M. (Eds.), Food Security in Southern Africa. Causes and Responses from the Region, pp. 67–88. https://hal.science/hal-00793066.

Burki, T., 2022. Humanitarian crisis in Tigray amidst civil war. Lancet Infect. Dis. 22 (6), 774–775. https://doi.org/10.1016/S1473-3099(22)00304-8.

Byaruhanga, C., 2022. Ethiopia's Tigray conflict: nasa shows how a war zone faded from space. In: BBC News – Ethiopian Civil War. https://www.bbc.com/news/world-africa-63315388.

Carranza, F., Treakle, J., 2014. Land, Territorial Development and Family Farming in Angola. A Holistic Approach to Community-Based Natural Resource Governance: the Cases of Bie, Huambo, and Huila Provinces. Food and Agriculture Organization of the United Nations.

Certini, G., Scalenghe, R., Woods, W.I., 2013. The impact of warfare on the soil environment. Earth Sci. Rev. 127, 1–15. https://doi.org/10.1016/j.earscirev.2013.08.009.

Chowdhury, P.R., Medhi, H., Bhattacharyya, K.G., Hussain, C.M., 2023. Severe Deterioration in Food-Energy-Ecosystem Nexus Due to Ongoing Russia-Ukraine War: A Critical Review, 166131. https://doi.org/10.1016/j.scitotenv.2023.166131. Science of The Total Environment.

CNN, 2021. Blinken: Acts of 'ethnic Cleansing' Committed in Western Tigray. https://edition.cnn.com/2021/03/10/politics/blinken-tigray-ethnic-cleansing/index.html.

Conflict and Environment Observatory (CEOBS), 2020. Eyes in the sky – Earth observations to monitor conflict and environment: Tracking the environmental dimensions of armed conflicts from space. https://ceobs.org/eyes-in-the-sky-earth-observations-to-monitor-conflict-and-environment/ (Accessed 6 July 2023).

Conflict and Environment Observatory (CEOBS), 2022. Report: the War in Tigray Is Undermining its Environmental Recovery. https://ceobs.org/the-war-in-tigray-is-undermining-its-environmental-recovery/. (Accessed 6 July 2023).

Costanza, R., De Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski, I., et al., 2014. Changes in the global value of ecosystem services. Global Environ. Change 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

Daiyoub, A., Gelabert, P., Saura-Mas, S., Vega-Garcia, C., 2023. War and deforestation: using remote sensing and machine learning to identify the war-induced deforestation in Syria 2010–2019. Land 12 (8), 1509. https://doi.org/10.3390/land12081509.

De Waal, A., 1991. Evil days: Thirty years of war and famine in Ethiopia. Human Rights Watch.

De Waal, A., 2015. The Real Politics of the Horn of Africa: Money, War and the Business of Power. John Wiley & Sons.

De Waal, A., 2021. The Mango Orchards of Zamra, Tigray. https://sites.tufts.edu/reinventingpeace/2021/03/03/the-mango-orchards-of-zamra-tigray/. (Accessed 5 July 2023).

Demissie, B., Nyssen, J., Annys, S., Negash, E., Gebrehiwet, T., Abay, F., Wolff, E., 2022. Geospatial solutions for evaluating the impact of the Tigray conflict on farming. Acta Geophys. 70 (3), 1285–1299. https://doi.org/10.1007/s11600-022-00779-7.

Eniang, E.A., Haile, A., Yihdego, T., 2007. Impacts of landmines on the environment and biodiversity. Envtl. Pol'y & L. 37, 501.

Ethiopian Monitor, 2021. Ethiopia to Offer a Billion Tree Seedlings to Neighboring Nations. https://ethiopianmonitor.com/2021/05/22/ethiopia-to-offer-a-billion-tree-seedlings-to-neighboring-nations/ (Accessed 6 July 2023).

Falk, R., 1989. Revitalizing International Law. Iowa University Press, Ames.

Feng, S., Fan, F., 2019. A hierarchical extraction method of impervious surface based on NDVI thresholding integrated with multispectral and high-resolution remote sensing imageries. IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sens. 12 (5), 1461–1470. https://doi.org/10.1109/JSTARS.2019.2909129.

Fensham, R.J., Fairfax, R.J., Archer, S.R., 2005. Rainfall, land use and woody vegetation cover change in semi-arid Australian savanna. J. Ecol. 93 (3), 596–606. https://doi.org/10.1111/j.1365-2745.2005.00998.x.

Fiseha, A., 2023. Tigray: a nation in search of statehood? Int. J. Minor. Group Right. 1 (aop), 1–47. https://doi.org/10.1163/15718115-bja10110.

Fleming, S., 2021. What Is Ecocide and Can it Be Prosecuted by the International Criminal. https://www.weforum.org/agenda/2021/07/ecocide-environmental-harm-international-crime/.

Food and Agriculture Organization (FAO), 2021. Emergency Livelihood Support for Conflict-Affected Communities in Ethiopia's Tigray Region, 06/07/2021. https://www.fao.org/resilience/news-events/detail/en/c/1415016/.

Funk, C., et al., 2015. The climate hazards infrared precipitation with stations — a new environmental record for monitoring extremes. Sci. Data 21. https://doi.org/10.1038/sdata.2015.66.

Garzón, F.A.M., Valánszki, I., 2020. Environmental armed conflict assessment using satellite imagery. J. Environ. Geogr. 13 (3–4), 1–14. https://doi.org/10.2478/jengeo-2020-0007.

Gebregziabher, G., Abera, D.A., Gebresamuel, G., Giordano, M., Langan, S., 2016. In: An Assessment of Integrated Watershed Management in Ethiopia. Colombo, Sri Lanka: International Water Management Institute (IWMI). 28pp. (IWMI Working Paper 170).

Gebrekirstos, A., Birhane, E., 2023. The war on Tigray wiped out decades of environmental progress: how to start again. The Conversation. https://theconversation.com/the-war-on-tigray-wiped-out-decades-of-environmental-progress-how-to-start-again-201062. (Accessed 8 July 2023).

Gebremeskel, K., Teka, K., Birhane, E., Negash, E., 2019. The role of integrated watershed management on soil-health in northern Ethiopia. Acta Agric. Scand. Sect. B Soil Plant Sci 69 (8), 667–673. https://doi.org/10.1080/09064710.2019.1639806.

Ghebreyohannes, T., Nyssen, J., Negash, E., Meaza, H., Tesfamariam, Z., Frankl, A., Abay, F., 2022. Challenges and resilience of an indigenous farming system during wartime (Tigray, North Ethiopia). Agron. Sustain. Dev. 42 (6), 116. https://doi.org/10.1007/s13593-022-00812-5.

Gidey, E., Dikinya, O., Sebego, R., Segosebe, E., Zenebe, A., Mussa, S., Birhane, E., 2023. Land use and land cover change determinants in raya valley, Tigray, northern Ethiopian highlands. Agriculture 13 (2), 507. https://doi.org/10.3390/agriculture13020507.

Gorsevski, V., Kasischke, E., Dempewolf, J., Loboda, T., Grossmann, F., 2012. Analysis of the Impacts of armed conflict on the Eastern Afromontane forest region on the South Sudan—Uganda border using multitemporal Landsat imagery. Rem. Sens. Environ. 118, 10–20. https://doi.org/10.1016/j.rse.2011.10.023.

Hadgu, K.M., Bishaw, B., Iiyama, M., Birhane, E., Negussie, A., Davis, C.M., Bernart, B., 2019. Climate-Smart Agriculture: Enhancing Resilient Agricultural Systems, Landscapes, and Livelihoods in Ethiopia and beyond. World Agroforestry (ICRAF), Nairobi, Kenya, p. 251. https://www.worldagroforestry.org/publication/climate-smart-agriculture-enhancing-resilient-agricultural-systems-landscapes-and-0.

Hagazi, N., Gebrekirstos, A., Birhane, E., Bongers, F., Kelly, R., Bräuning, A., 2020. Land Restoration Requires a Shift from Quantity to Quality: Lessons from Tigray, Ethiopia. ETFRN and Tropenbos International, Wageningen, the Netherlands. https://library.wur.nl/WebQuery/wurpubs/fulltext/549190.

Handl, G., 2012. Declaration of the united nations conference on the human environment (stockholm declaration), 1972 and the rio declaration on environment and development, 1992. United Nations Audiovisual Library of International Law 11 (6). https://www.globalhealthrights.org/wp-content/uploads/2014/06/Stockholm-Declaration1.pdf.

Hawinkel, P., Thiery, W., Lhermitte, S., Swinnen, E., Verbist, B., Van Orshoven, J., Muys, B., 2016. Vegetation response to precipitation variability in East Africa controlled by biogeographical factors. J. Geophys. Res.: Biogeosciences 121 (9), 2422–2444. https://doi.org/10.1002/2016JG003436.

Hendrie, B., 1994. Relief aid behind the lines: the cross-border operation in Tigray. London, U.K., Zed Books. In: Macrae, J., Zwi, A. (Eds.), War and Hunger: Rethinking International Responses to Complex Emergencies, pp. 125–138.

Higgins, P., 2015. Eradicating Ecocide, second ed. Shepheard-Walwyn.

Hishe, H., Giday, K., Fremout, T., Negussie, A., Muys, B., 2022. Recruitment credit cannot compensate for extinction debt in a degraded dry Afromontane forest. J. Veg. Sci. 33 (3), e13134 https://doi.org/10.1111/jvs.13134.

Houghton, R.A., Skole, D.L., 1990. Changes in the carbon cycle between 1700 and 1985. In: Turner, B.L. (Ed.), The Earth Transformed by Human Action. Cambridge.

Human Rights Watch (HRW), 2022. "We Will Erase You from This Land": Crimes against Humanity and Ethnic Cleansing in Ethiopia's Western Tigray Zone. https://www.hrw.org/report/2022/04/06/we-will-erase-you-land/crimes-against-humanity-and-ethnic-cleansing-ethiopias.

Human Rights Watch (HRW), 2023. Ethiopia: Ethnic Cleansing Persists under Tigray Truce. Rights Abusers in Western Tigray Zone Face No Accountability for Torture, Forced Expulsions. https://www.hrw.org/news/2023/06/01/ethiopia-ethnic-cleansing-persists-under-tigray-truce.

Hurni, H., Tato, K., Zeleke, G., 2005. The implications of changes in population, land use, and land management for surface runoff in the upper Nile basin area of Ethiopia. Mt. Res. Dev. 25 (2), 147–154. https://doi.org/10.1659/0276-4741(2005)025[0147:TIOCIP]2.0.CO;2.

Ibreck, R., de Waal, A., 2022. Introduction: situating Ethiopia in genocide debates. J. Genocide Res. 24 (1), 83–96. https://doi.org/10.1080/14623528.2021.1992920.

Ilstedt, U., Tobella, A.B., Bazié, H.R., Bayala, J., Verbeeten, E., Nyberg, G., Sanou, J.L., Benegas, L., Murdiyarso, D., Laudon, H., Sheil, D., Malme, A., 2016. Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Sci. Rep. 6 https://doi.org/10.1038/srep21930. Article No. 21930.

International Committee of the Red Cross (ICRC), 1977a. Protocol Additional to the Geneva Conventions of 12 August 1949, and Relating to the Protection of Victims of International Armed Conflicts (Protocol I), 8 June 1977. International Humanitarian Law Databases. https://ihl-databases.icrc.org/en/ihl-treaties/api-1977/article-54?activeTab=default. (Accessed 26 June 2023).

International Committee of the Red Cross (ICRC), 1977b. Protocol Additional to the Geneva Conventions of 12 August 1949, and Related to the Protection of Victims of Non-international Armed Conflicts (Protocol II) of 8 June 1977.

International Committee of the Red Cross (ICRC), 2022. Ethiopia: Rare Footage from Tigray Shows Health Crisis. https://www.icrcnewsroom.org/preview/en/2045/ethiopia-rare-footage-from-tigray-shows-health-crisis/2924. (Accessed 5 July 2023).

International Organisation for Migration (IMO), 2021. Household level intention survey. Tigray Region, Ethiopia. https://dtm.iom.int/sites/g/files/tmzbdl1461/files/reports/Household%20Level%20Intention%20Survey%20in%20Tigray%20%28July%202021%29%20v3.pdf. (Accessed 7 July 2023).

James, J., Kanaan, R., Malley, M., Roule, T., Thomson, J., 2003. Conflict timber: dimensions of the problem in asia and Africa volume II. Asian Cases.

Juszak, I., Erb, A.M., Maximov, T.C., Schaepman-Strub, G., 2014. Arctic shrub effects on NDVI, summer albedo and soil shading. Rem. Sens. Environ. 153, 79–89. https://doi.org/10.1016/j.rse.2014.07.021.

Keen, D., 1991. A disaster for whom?: local interests and international donors during famine among the dinka of Sudan. Disasters 15 (2), 150–165. https://doi.org/10.1111/j.1467-7717.1991.tb00444.x.

Keen, D., 1994. In: Macrae, J., Zwi, A. (Eds.), The Functions of Famine in Southwestern Sudan: Implications for Relief. War and Hunger: Rethinking International Responses to Complex Emergencies. Zed Books, London, U.K., pp. 111–124

Kuol, L.B.D., 2014. Confronting civil war: the level of resilience in abyei area during Sudan's civil war in the 1990s. Civ. Wars 16 (4), 468–487. https://doi.org/10.1080/13698249.2014.981943.

Laakkonen, S., 2004. War—an ecological alternative to peace? Indirect impacts of World War II on the Finnish environment. Natural Enemy, Natural Ally: Toward an Environmental History of Warfare 175–194.

Lawrence, M.J., Stemberger, H.L., Zolderdo, A.J., Struthers, D.P., Cooke, S.J., 2015. The effects of modern war and military activities on biodiversity and the environment. Environ. Rev. 23 (4), 443–460. https://doi.org/10.1139/er-2015-0039.

Machlis, G.E., Hanson, T., 2008. Warfare ecology. BioScience 58 (8), 729–736. https://doi.org/10.1641/B580809.

Macrae, J., Zwi, A., 1994. In: Macrae, J., Zwi, A. (Eds.), Famine, Complex Emergencies and International Policy in Africa: an Overview. War and Hunger: Rethinking International Responses to Complex Emergencies. Zed Books, London, U.K., pp. 6–36

Mahreen, K., 2022. The Environmental Impacts of War and Conflict. https://opendocs.ids.ac.uk/opendocs/handle/20.500.12413/17466.

Mapulanga, A.M., Naito, H., 2019. Effect of deforestation on access to clean drinking water. Proc. Natl. Acad. Sci. U.S.A. 116 (17), 8249–8254. https://doi.org/10.1073/pnas.1814970116.

Marzolff, I., Kirchhoff, M., Stephan, R., Seeger, M., Ait Hssaine, A., Ries, J.B., 2022. Monitoring dryland trees with remote sensing. Part A: beyond CORONA—historical HEXAGON satellite imagery as a new data source for mapping open-canopy woodlands on the tree level. Front. Environ. Sci. 10, 896702 https://doi.org/10.3389/fenvs.2022.896702.

McNeill, J.R., 2001. Something New under the Sun: an Environmental History of the Twentieth-Century World (The Global Century Series). WW Norton & Company.

Mhanna, S., Halloran, L.J., Zwahlen, F., Asaad, A.H., Brunner, P., 2023. Using machine learning and remote sensing to track land use/land cover changes due to armed conflict. Sci. Total Environ. 898, 165600 https://doi.org/10.1016/j.scitotenv.2023.165600.

Munro, R.N., Woldegerima, T., Hailu, B., Zenebe, A., Gebremedhin, Z., Hailemichael, A., Nyssen, J., 2019. A history of soil and water conservation in Tigray. In: Geo-trekking in Ethiopia's Tropical Mountains: the Dogu'a Tembien District. https://doi.org/10.1007/978-3-030-04955-3_32, 477-493.

Negash, E., Birhane, E., 2023. War and Siege Inflicted Damage on Tigray's Ecosystem. *Ethiopia Insight*. https://www.ethiopia-insight.com/2023/02/22/war-and-siege-inflicted-damage-on-tigrays-ecosystem/.

Negash, E., Gebresamuel, G., Embaye, T.A., Nguvulu, A., Meaza, H., Gebrehiwot, M., et al., 2020a. Impact of headwater hydrological deficit on the downstream flood-based farming system in northern Ethiopia. Irrigat. Drain. 69 (3), 342–351. https://doi.org/10.1002/ird.2413.

Negash, E., Getachew, T., Birhane, E., Gebrewahed, H., 2020b. Ecosystem service value distribution along the agroecological gradient in north-central Ethiopia. Earth Systems and Environment 4, 107–116. https://doi.org/10.1007/s41748-020-00149-7.

News24, 2023. In: Tigray, Abandoned Explosives Continue the War against Civilians after the Fighting Is Done. https://www.news24.com/news24/africa/news/in-tigray-abandoned-explosives-continue-the-war-against-civilians-after-the-fighting-is-done-20231006. (Accessed 19 October 2023).

Ngussie, H.G., Hailu, T.G., 2023. Tigray War Put Honey Bees in Peril. Bee World, pp. 1–5. https://doi.org/10.1080/0005772X.2023.2201086.

NPR, 2021. How 165 Words Could Make Mass Environmental Destruction an International Crime. https://www.npr.org/2021/06/27/1010402568/ecocide-environment-destruction-international-crime-criminal-court?t=1661116993213.

Nyssen, J., 2021. In: Catastrophe Stalks Tigray, Again. Ethiopia Insight, 19 February 2021. https://www.ethiopia-insight.com/2021/02/19/catastrophe-stalks-tigray-again/.

Nyssen, J., Demissie, B., 2023. Administrative and ethno-linguistic boundaries of western Tigray (Ethiopia) since 1683. J. Maps 19 (1), 2257249. https://doi.org/10.1080/17445647.2023.2257249.

Nyssen, J., Frankl, A., Haile, M., Hurni, H., Descheemaeker, K., Crummey, D., et al., 2014. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. Sci. Total Environ. 485, 164–179. https://doi.org/10.1016/j.scitotenv.2014.03.052.

Nyssen, J., Negash, E., Van Schaeybroeck, B., Haegeman, K., Annys, S., 2022. Crop cultivation at wartime–plight and resilience of Tigray's agrarian society (north Ethiopia). Defence Peace Econ. 34 (5), 618–645. https://doi.org/10.1080/10242694.2022.2066420.

Ouyang, Y., Jin, W., Grace, J.M., Obalum, S.E., Zipperer, W.C., Huang, X., 2019. Estimating impact of forest land on groundwater recharge in a humid subtropical watershed of the Lower Mississippi River Alluvial Valley. J. Hydrol.: Reg. Stud. 26, 100631 https://doi.org/10.1016/j.ejrh.2019.100631.

Pereira, P., Bašić, F., Bogunovic, I., Barcelo, D., 2022. Russian-Ukrainian war impacts the total environment. Sci. Total Environ. 837, 155865.

Plaut, M., 2013. How unstable is the horn of Africa? Rev. Afr. Polit. Econ. 40 (136), 321–330. https://doi.org/10.1080/03056244.2013.797760.

Plaut, M., Vaughan, S., 2023. Understanding Ethiopia's Tigray War. Hurst Publishers.

Rawtani, D., Gupta, G., Khatri, N., Rao, P.K., Hussain, C.M., 2022. Environmental damages due to war in Ukraine: a perspective. Sci. Total Environ. 850, 157932 https://doi.org/10.1016/j.scitotenv.2022.157932.

Rettberg, S., Beckmann, G., Minah, M., Schelchen, A., 2017. Ethiopia's Arid and Semi-arid Lowlands: towards Inclusive and Sustainable Rural Transformation. Albrecht Daniel Thaer-Institut für Agrar-und Gartenbauwissenschaften.

Reuveny, Rafael, Mihalache-O'Keef, Andreea S., Quan, Li, 2010. The effect of warfare on the environment. J. Peace Res. 47 (6), 749–761. https://doi.org/10.1177/0022343310382069.

Román, M.O., Stokes, E.C., Shrestha, R., Wang, Z., Schultz, L., Carlo, E.A.S., et al., 2019. Satellite-based assessment of electricity restoration efforts in Puerto Rico after Hurricane Maria. PLoS One 14 (6), e0218883. https://doi.org/10.1371/journal.pone.0218883.

Sands, P., Peel, J., Fabra, A., MacKenzie, R., 2018. Principles of International Environmental Law. Cambridge University Press.

Santora, M., 2023. As Dead Dolphins Wash Ashore, Ukraine Builds a Case of Ecocide against Russia. The New York Times. https://www.nytimes.com/2023/08/17/world/europe/russia-war-dolphin-deaths-ukraine.html. (Accessed 18 July 2023).

Schindler, D., Toman, J., 2004. Convention on the prohibition of military or any other hostile use of environmental modification techniques. In: The Laws of Armed Conflicts. Brill Nijhoff, pp. 163–177. https://doi.org/10.1163/9789047405238_021.

Serhii, A.S., Vyshnevskyi, V.I., Olena, P.B., 2022. The use of remote sensing data for investigation of environmental consequences of Russia-Ukraine war. Journal of Landscape Ecology 15 (3), 36–53. https://doi.org/10.2478/jlecol-2022-0017.

Shumilova, O., Tockner, K., Sukhodolov, A., Khilchevskyi, V., De Meester, L., Stepanenko, S., et al., 2023. Impact of the Russia–Ukraine armed conflict on water resources and water infrastructure. Nat. Sustain. 6 (5), 578–586. https://doi.org/10.1038/s41893-023-01068-x.

Silleos, N.G., Alexandridis, T.K., Gitas, I.Z., Perakis, K., 2006. Vegetation indices: advances made in biomass estimation and vegetation monitoring in the last 30 years. Geocarto Int. 21 (4), 21–28. https://doi.org/10.1080/10106040608542399.

Smil, V., 1990. Planetary Warming: Realities and Responses. *Population And Development Review*, pp. 1–29. https://www.jstor.org/stable/1972527.

Sohn, L.B., 1973. Stockholm declaration on the human environment, the. Harv. Int'l. LJ 14, 423. https://www.jstor.org/stable/1972527.

Solokha, M., Pereira, P., Symochko, L., Vynokurova, N., Demyanyuk, O., Sementsova, K., et al., 2023. Russian-Ukrainian War Impacts on the Environment. Evidence from the Field on Soil Properties and Remote Sensing. Science of The Total Environment, 166122. https://doi.org/10.1016/j.scitotenv.2023.16612.

Solomon, N., Birhane, E., Gordon, C., Haile, M., Taheri, F., Azadi, H., Scheffran, J., 2018. Environmental impacts and causes of conflict in the Horn of Africa: a review. Earth Sci. Rev. 177, 284–290. https://doi.org/10.1016/j.earscirev.2017.11.016.

Springgay, E., Ramirez, S.C., Janzen, S., Brito, V.V., 2019. Forest-water nexus: an international perspective. Forests 10. https://doi.org/10.3390/f10100915. Article No. 915.

Sticher, V., Wegner, J.D., Pfeifle, B., 2023. Toward the remote monitoring of armed conflicts. PNAS Nexus 2 (6), pgad181. https://doi.org/10.1093/pnasnexus/pgad181.

Stop Ecocide Foundation, 2021. Independent Expert Panel for the Legal Definition of Ecocide. Commentary and Core Text. June 2021. https://www.stopecocide.earth/expert-drafting-panel.

Sun, L., Yang, L., Hao, L., Fang, D., Jin, K., Huang, X., 2017. Hydrological effects of vegetation cover degradation and environmental implications in a semiarid temperate Steppe, China. Sustainability 9 (2), 281. https://doi.org/10.3390/su9020281.

Teferi, H.H., 2021. Restoration Potential of Desa'a Forest, a Large Threatened Dryland Forest in Tigray, Northern Ethiopia. Doctoral dissertation, KU Leuven, Belgium.

The Reporter, 2022. ECX to trade wheat after 15 years break. https://www.thereporterethiopia.com/27316/. (Accessed 7 July 2023).

United Nations Human Rights Council (Unhrc), 2023. International community must ensure accountability and protection for civilians caught in Ethiopia conflict, UN commission says final report. https://www.ohchr.org/en/press-releases/2023/10/international-community-must-ensure-accountability-and-protection-civilians?sub-site=HRC. (Accessed 19 October 2023).

United States Department of Agriculture (Usda), 1998. Global Desertification Vulnerability Map updated on. https://www.change-climate.com/Conferences_Events_Exhibitions_Climate_Change/Desertification/COP10_Changwon_South_Korea_2011_UN_Desertification_United_Nations_Conferences_Of_The_Parties.htm. (Accessed 8 September 2003).

Vanden Bempt, T., Annys, S., Negash, E., Ghekiee, R., Nyssen, J., 2021. In: Tigray: One Year of Conflict – Casualties of the Armed Conflict, 2020-2021 – Tigray (Ethiopia). https://doi.org/10.5281/zenodo.5804251. Ghent University, Department of Geography (Ghent, Belgium) & Every Casualty Counts (London (U.K.

VOA news, 2022. የቃፍታሸራሮብሔራዊፓርክከፍተኛጉዳትእንደደረሰበትተገለፀ [KaftaSheraro National Park has been heavily damaged]. VOA Amharic August 11, 2022. https://amharic.voanews.com/a/6697911.html.

Vučinić, J., Beronja, B., Vučinić, Z., 2012. The Impact of War on the Environment, pp. 255–260.

Weldegiargis, A.W., Abebe, H.T., Abraha, H.E., Abrha, M.M., Tesfay, T.B., Belay, R.E., et al., 2023. Armed conflict and household food insecurity: evidence from war-torn Tigray, Ethiopia. Conflict Health 17 (1), 22. https://doi.org/10.1186/s13031-023-00520-1.

Whiting, A., 2017. Ethiopia's Tigray Region bags gold award for greening its drylands. Reuters August 22, 2017. https://www.reuters.com/article/us-land-farming-idUSKCN1B21CT.

Wight, P., 2022. Many Hurdles to Peace in Tigray Remain after Pretoria and Nairobi Deals. Ethiopia Insight. https://www.ethiopia-insight.com/2022/11/25/many-hurdles-to-peace-in-tigray-remain-after-pretoria-and-nairobi-deals/. (Accessed 7 July 2023).

Woolf, D., Solomon, D., Lehmann, J., 2018. Land restoration in food security programmes: synergies with climate change mitigation. Clim. Pol. 18 (10), 1260–1270. https://doi.org/10.1080/14693062.2018.1427537.

Yale Law School, 2023. "All of us are in constant hunger" Ethiopia's responsibility for starvation in Tigray. Lowenstein Clinic Finds Ethiopia and Allies Responsible for Mass Starvation in Tigray. Allard K. Lowenstein International Human Rights Clinic. https://law.yale.edu/yls-today/news/lowenstein-clinic-finds-ethiopia-and-allies-responsible-mass-starvation-tigray (Accessed 7 July 2023).

Yeo, S., 2020. Ecocide: Should killing nature be a crime? BBC Future. https://www.bbc.com/future/article/20201105-what-is-ecocide (Accessed 7 July).

Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., Santoro, M., Fritz, S., Lesiv, M., Herold, M., Tsendbazar, N.E., Xu, P., Ramoino, F., Arino, O., 2022. *ESA WorldCover* 10 M 2021 V200. https://doi.org/10.5281/zenodo.7254221. https://worldcover2021.esa.int/.

Zhang, C., Hu, Q., Su, W., Xing, C., Liu, C., 2023. Satellite spectroscopy reveals the atmospheric consequences of the 2022 Russia-Ukraine war. Sci. Total Environ. 869, 161759 https://doi.org/10.1016/j.scitotenv.2023.161759.

Zwijnenburg, W., Ballinger, O., 2023. Leveraging emerging technologies to enable environmental monitoring and accountability in conflict zones. Int. Rev. Red Cross 1–25. https://doi.org/10.1017/S1816383123000383.