

Photographic record of land degradation and resilience in Dogu'a Tembien after the shock of the Tigray war (northern Ethiopia)

by

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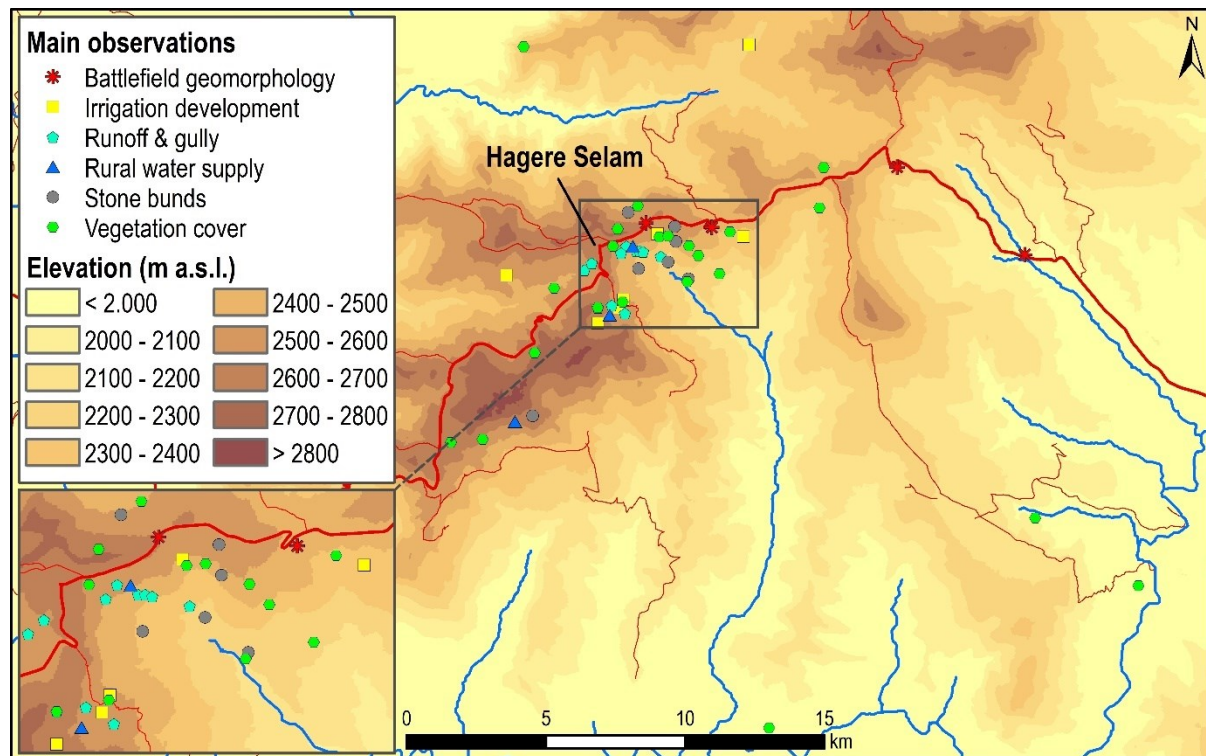
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Executive summary

Following two years of combat, blockade, and power outage, the Tigray war in northern Ethiopia has had a substantial negative impact on the environment (2020–2022). This photographic dataset, part of a rare study carried out by the same research team before and after a war, compares 26-year legacy data on land degradation (Table 1), with post-war observations at 56 sites in the Dogu'a Tembien district of Tigray (13°39'N, 39°30'E), at elevations ranging from 1600 to 2800 meters.



Location of study sites. Coordinates of map corners: (13.722°N, 39.095°E), (13.482°N, 39.391°E)

Land conservation and the Tigray War

Large-scale land conservation initiatives have been made in the study region since the 1980s, which is why the people of Tigray received the UN-backed World Future Policy Gold Award (Desertification) in 2017 [1].

Then came the Tigray war, which began on November 4, 2020, and formally ended on November 2, 2022, when the Cessation of Hostilities Agreement was signed. In the first part of 2021, armed troops from the federal government of Ethiopia, the adjacent Amhara region, and Eritrea advanced heavily into Tigray, engaging in combat with the forces of the Tigray regional government. After that, the region was under a 360-degree blockade, cutting off trade, aid, travel, banking, and connection with the outside world. This blockade lasted until the end of 2022.

The war included major battles in the study area, and massacres resulting in 70–110 civilian deaths, and the shelling of the Togogwa market with at least 64 deaths [2]. The agricultural system was directly impacted by the prohibition against plowing until then end of June 2021, and the scarcity of commercial fertilizers and seeds [3]. Market activity almost stopped [4, 5]. A severe state of hunger was brought on by a decrease in food production and availability [6, 7].

Land deterioration resulted from the cessation of official land restoration efforts and the overexploitation of the environment by the occupants and troops for survival. The cessation of public services, such as power for houses and businesses, led to a rise in the need for firewood and charcoal, which in turn caused deforestation [3, 8, 9].

It is crucial to note that there was no drought during the Tigray War era. In Dogu'a Tembien, the years 2017 to 2022 (shortly before and during the war) all saw yearly rainfall in the range of 750–850 mm, which is on the higher end of the historical record. Seasonality-wise, rainfall in nearly every month from 2019 to 2022 was at or above average. May 2022, when the spring rains failed, is the primary anomaly. Therefore, a meteorological factor (a lack of rain) cannot be the source of the environmental stress of 2021 and 2022. However, invasive species like *Salvia tiliifolia* have found an ecological niche due to long-term trends of rising temperatures and increased precipitation (Figure 9).

Methodology

With 30 years of environmental research experience in Tigray, we remained as a lone research team after the start of the war and collected ground data at previous research sites during the war. This culminated in international partners returning to the Dogu'a Tembien district in 2023 after they had been absent for four years due to coronavirus restrictions and the Tigray War. We visited 56 previously investigated sites—which have been documented in 45 prior publications—through transect walks, where we mostly made qualitative observations and discussions regarding the processes of land degradation and recovery (Table 1). This included degradation processes like sheet and rill erosion [10], gully erosion [11], landslides [12, 13], deforestation [14], as well as the most common rehabilitation approaches, i.e. stone bunds [15], check dams [16], exclosures [17], improved hydrological cycle [18], and integrated catchment management [19]. Local farmers and other village residents, along with experts who either reside in or have a good understanding of the research area, participated in the group observations.

We particularly looked into the condition of the stone bunds in 31 areas, in which they were categorized into five different categories: perfect, acceptable, requiring minor maintenance, needing significant maintenance, or necessitating complete rebuilding.

The qualitative observations were supported by previous research employing remote sensing studies conducted during the Tigray War and collaborative field campaigns with Mekelle University geographers, which is located around 50 km from the subject area [3, 5, 8, 20].

Preliminary findings

The dataset demonstrates that, in contrast to the warfare and environmental devastation that occurred in Tigray in the 1980s, simple soil conservation measures like stone bunds (Figures 13 to 16, Table 2), check dams (Figures 25 to 27), and forest preservation (Figures 4 to 8) have since proven to be an essential barrier against the effects of the armed conflict.

On the other hand, the battlefields and downriver banks have undergone notable geomorphic modifications (Figures 17 and 18). The land resilience that has been observed can be attributed to a strong feeling of community, self-reliance, and a long history of land management. Our qualitative findings indicate a wealth of opportunities for further investigation.

Besides the mentioned positives, a drawback is the easy resurgence of open access to communal land (“tragedy of the commons”) (Figures 1 to 3). The situation is even much worse in other districts surrounding towns like Shire where a total of one million internally displaced people live, or where Amhara and Eritrean military are occupying them, and where extensive fuelwood collection continues to occur [8].

Key words: exclosure; farmer-led irrigation; gully; land rehabilitation; soil erosion; stone bunds

Overview of observed sites and photographic dataset

Table 1. Study sites from previous research revisited in October 2023-January 2024

Name	Latitude (°N)	Longitude (°E)	2023 observations on	Photo number; references of earlier studies on related topic at the same site
Gra Arho plantation	13.65016	39.17661	<i>Salvia tiliifolia</i> invasion; massive eucalypt harvesting	8, 9 [21]
Gra Arho village	13.65016	39.18101	Effects of village expansion on runoff: innovative irrigation	21, 33 [22-24]
Harena torrent	13.64801	39.17923	Gully control measures; log dams	27 [21, 25]
Gra Arho spring	13.65007	39.18310	Spring development project	29 [26]
Footpath Gra Arho to Golab	13.64867	39.18429	Concentrated runoff	21 [21, 22]
Golab	13.64866	39.18536	Rangeland degradation; stone bunds; surface runoff	22 [22-24, 27]
Golab	13.64839	39.18650	Gully development	[21, 23, 28]
Argaqa	13.64686	39.19238	Stone bunds, gully erosion	16 [18, 21-24, 28-33]
May Shewate	13.64507	39.19481	Gully bottom irrigaton; stone bunds	[18, 30, 34, 35]
Habdi Luqmut	13.63855	39.20118	Well managed community forest	6 [10, 29, 32, 36, 37]
Hechi (Shikha)	13.63964	39.20156	Stone bunds	[10, 31, 32]
Hechi (Ba'ikhel)	13.64117	39.21188	Traditional agroforestry; stone bunds	[29, 32, 36, 38]
Igri Mullo	13.64714	39.20486	Exclosure management	38 [39, 40]
Hagere Selam sand dam	13.64466	39.16949	Runoff buffering	25 [21]
Addi Selam	13.64251	39.16700	Gully stabilization	26 [21, 23, 29, 37]
Mehati Lahma	13.63659	39.15703	Forest remnant, Eucalypt plantation	12 [41]
May Sa'iri	13.64078	39.14118	Vegetable gardens	37 [42]
Addi Qolqwal	13.65032	39.20176	Rill erosion due to cropland expansion on steep slope; <i>Salvia tiliifolia</i>	19 [37, 43]
West of Addi Qolqwal	13.65168	39.19736	Stone bunds	13 [18, 24, 30-32]
May Toqem (Addi Qolqwal)	13.65349	39.19492	Exclosure management; failed water project	[18, 30-32, 35]
May Ntebteb exclosure	13.65316	39.19187	Exclosure management, tree cutting, grazing, landslide	1 [13, 18, 30-32]
Zenaqo	13.65422	39.19130	Springs and irrigation	[18, 32-35]
Gra Mehaber	13.65648	39.19703	Stone bunds	14 [10, 30-32, 44]
Hagere Selam	13.65176	39.17400	Proposed geotourism office	[45]
Imba Zuw'ala	13.65584	39.17805	Eucalypt harvesting, grazing	10, 11 [46]
Ziban Kerkata	13.66115	39.18155	Stone bunds	[22]
Khunale	13.66332	39.18478	Exclosure management, tree cutting, grazing	2 [40, 47, 48]

Harhar	13.65771	39.18754	Gully erosion at battlefield	[28, 49]
Maltmasha	13.63030	39.17145	New settlement, enhanced drainage, eucalypt plantation with trenches for water harvesting	23 [50]
May Zahla exotic tree experimental site	13.63030	39.17145	Tree cutting, grazing	3 [24]
May Zahla nursery and orchard	13.62516	39.17145	Apple tree management	34 [51]
Rubadera	13.62784	39.17539	Hand pump; diversions for irrigation	30 [50]
Dingilet homestead gardens	13.63017	39.17863	Vegetable growing; apple tree reproduction	35, 36 [50]
Dingilet Kwiha	13.62843	39.18052	Gully erosion	[28]
Dingilet private eucalypt plantations	13.63209	39.17965	(absence of) eucalypt harvesting	[50]
May Mehtsab	13.63289	39.17989	Diversion canal for irrigation	[24]
Dingilet road incision	13.63100	39.17608	Gully development	24 [21]
Harena	13.64288	39.18502	Stone bunds	15 [24]
Debremedhanit (Itay Sara)	13.71485	39.14688	Exclosure management	7 [42]
Afedena	13.67565	39.27087	Battlefield geomorphology; farmland expansion	17, 20 [16, 52]
Tukhul gully	13.64727	39.31317	Gully expansion	17 [53]
Agerba	13.61556	39.15054	Eucalypt plantation, gully erosion	[28]
Wunana	13.71545	39.22179	Irrigation development	31 [42]
Addi Lihtsi	13.49389	39.22819	Dry forest dominated by incense trees	[54]
Togogwa	13.56190	39.31660	Status of exclosures	[42]
Kolal	13.53985	39.35079	Status of exclosures	[42]
Addi Qolqwal	13.65629	39.20934	Stone bunds, gully development	18 [16, 55]
Addi Qolqwal exclosure	13.65482	39.21544	Exclosure management	4 [39]
May Bi'ati	13.65334	39.21976	Gully rehabilitation, irrigation	32 [46, 56, 57]
Gemgema	13.66255	39.24512	Vegetation status, <i>Salvia tiliifolia</i>	[42]
Addi Qoylo	13.67569	39.24645	Road erosion, overgrazing, exclosure management	5 [22, 28, 58]
Mashih	13.59520	39.14977	Stone bunds	[24]
May Toqem (Mezegat)	13.59327	39.14389	Spring development project	28 [59]
Seret	13.58755	39.13319	Forest management	[60]
Inda Maryam vertisols	13.58664	39.12272	Overgrazing	[61]

Photographic data set

Woody vegetation



Figure 1. A conspicuous myrtle tree (*Myrica salicifolia*) at the upper edge of the May Ntebteb enclosure. At left, hosting the participants of the international HighLand2006 scientific conference [62, 63] (photo © Neil Munro); at right, its major branches were harvested by individuals in 2021 – a saw was used at night, so that cutting was silent, in contrast to the commonly used axe (photo in October 2023).



Figure 2. In the Khunale enclosure [40, 47, 48], many trees have disappeared, particularly at its western side, closest to the village (foreground of the photo, at the foot of the cliff). The cutting started with the war. There was lawlessness and people went into the enclosure to cut trees, indigenous trees as well as eucalypts. The cutting stopped around the time of Cessation of Hostilities Agreement in November 2022. There is poor regrowth of the trees, because this enclosure remained open for grazing. Photo in November 2023.



Figure 3. The experimental tree plantation of Dingilet, from which the villagers do not directly benefit) has been largely depleted from its trees (various eucalypt species, peppertrees, mulberry, moringa, ...) and grazed short, whereas the adjacent apple tree nursery had been well preserved throughout the war (Figure 34). Both sites depend on the local branch of the Bureau of Agriculture, and between the end of 2020 up to end of 2023 no staff visited the site. Photo in October 2023.



Figure 4. In Addi Qolqwal's enclosure (left part of the photo, taken in November 2023) there has been some wood chopping, but probably not worse than before the war. Some branches were cut from eucalypts, but this tree is typically grown to provide wood. Saplings of *Dodonaea angustifolia* had emerged, and remarkably, the gully at the edge of the enclosure is well controlled by check dams and the woody vegetation that has grown in it since twenty years [39].



Figure 5. Along the rural road to Addi Qoylo gullies have occurred due to a lack of road maintenance since 2020 (left, looking upslope). The runoff path then leaves the road and enters into an enclosure managed by the “Trees For Farmers” [64] project (right, looking downslope). Though no salaries or payments were received during the war, the guards have continued protecting it and the enclosure stands nicely. The enclosure totally buffered the runoff coming from the road and the gully is discontinued and sediment is deposited. Photographs taken in November 2023.



Figure 6. The Habdi Luqmut forest in Hech'i [30, 32] remained in a good shape throughout the war period, as observed in October 2023. Farmers reported that during that difficult time they did not cut wood from their forests or enclosures, or from other trees far away from the village: “We all have trees on our farmland boundaries and when we need wood, we cut it from there”. They also said that they are located too far from Mekelle or even Hagere Selam to organize charcoal trade, like Togogwa did for instance.



Figure 8. In the Debre-medhanit (Itay Sara) enclosure, managed by the EthioTrees project [65], no wood harvesting or grazing occurred in 2020-2022. In 2022, during and despite the blockade of Tigray, the villagers of Tsili, to which the enclosure belongs, received 1 M ETB as carbon offset payment, that was shared between 589 households. As the communities directly benefit from keeping their enclosures intact through payments for carbon certificates, there are fines for anybody who cuts trees illegally. This rule was maintained throughout the war. Also, adjacent enclosures have been well kept, as villagers hope that these will be included in the carbon project in the future. Photo taken in January 2024.



Figure 8. In the Gra Arho eucalypt plantation, which is at the edge of Hagera Selam town, many trees have been cut in 2021 and 2022. Many people were without income, so those who could sell wood had money to survive. There was almost no electricity at that time and firewood fetched good prices. The dominant dry brown herbs are a new invasive weed, *Salvia tiliifolia* (see Figure 9). Photo taken in October 2023.



Figure 9. Since approx. 2019, *Salvia tiliifolia* has appeared in the study area, where it now occupies large areas, especially where soil is reworked, such as dumped soils, roadsides (here in Hagere Selam, along the old road to Mekelle, September 2024), building sites, but also in eucalypt plantations that were opened up due to war-related wood harvesting (Figure 8), and further down in fresh alluvium along rivers. The species is not toxic, but according to the farmers useless, and it occupies space. There is no local name for the plant, just “new weed”. On well-managed farmlands, one will generally not observe this weed because the farmers remove it very easily: easy to identify, easy to pick out. *S. tiliifolia* is now the main weed; it grows rapidly and even suppresses the other weeds. Native to Central America, it is a recent exotic invasive species in Ethiopia, first described in Ethiopia in 1996 [66]. It is now quite widespread over the Ethiopian highlands [67]. Its expansion into Dogu’a Tembien is relatively late. The wetter conditions in recent years (and even in the last decades), jointly with slowly increasing temperatures, may have contributed to the creation of a niche for the species, in line with observations of natural vegetation and crop belts that shift up the mountains in northern Ethiopia [68, 69]. The extent to which multiple traffic and war disturbances may have contributed to this spread is unknown.



Figure 10. Since 2023, it is not allowed anymore to cut trees from the eucalypt plantations. Special permission is however given to TDF soldiers (Tigray Defense Forces), who get insufficient logistics and hence obtain permission from district officials to harvest trees for firewood, here on the slopes of Imba Zuw'ala (November 2023).



Figure 11. The Imba Zuw'ala eucalypt plantation was established around 2000, on communal lands that had been expropriated and transferred to the Maychew Particleboard Factory [70], yet claimed by the community. Many trees were harvested in this plantation during the war. There is coppicing on all stools, which indicates that after some years, the eucalypt tree cover will be strong again. Drawback is however the free grazing in such places; especially goats browse young *Eucalyptus* leaves in periods of pasture scarcity and damage the coppicing trees [71], which hampers regrowth. In addition, the undergrowth, which is typically very poor under eucalypts, is further removed, and this leads to a stronger runoff response and erosion, and less infiltration. Photo in October 2023.



Figure 12. In the greenish Mehati Lahma gorge [41], the eucalypts have not been cut, in contrast to Gra Arho, or those along the main road. Whenever eucalyptus trees were cut for provisioning of armies, or for organized trade, it occurred in areas that are easily accessible, near towns, military camps or along roadsides. Photo in October 2023.

Stone bunds for soil and water conservation



Figure 13. Near Addi Qolqwal, almost all stone bunds stand in October 2023 as they were standing before the war [18, 30]. At several places we saw that farmers have maintained their stone bunds.



Figure 14. At Gra Mehaber, no overall collapse of the two-decades old stone bunds [10, 30-32, 44] was observed in October 2023. There are some small parts of stone bunds that have collapsed, even though no runoff had flown through it. The farmers' attitude is that they will wait whether the community comes to this area in the dry season and repairs it as part of the regular catchment management works, if not he will repair it himself by June, at sowing time (left). Another farmer showed a new stone bund that he constructed on his land, as he could not find off-farm employment at slack time and yet wanted to occupy his time usefully (right).



Figure 15. By October 2023, the stone bund landscape in the farmlands of Harena does not show evidence of any destroyed stone bunds, neither the existence of drainage lines induced by weaknesses in the bunds. The farmers have repaired any damage that may have occurred to these bunds near their village.



Figure 16. In the Argaqa area, all stone bunds, constructed in the years after 2000 [22, 23], were intact in October 2023. Overall, among the representative sample of 31 observed stone bunds (Table 2), 25 are in acceptable to perfect condition, four have collapsed in their upper part without generating concentrated runoff and two need rebuilding. Bunds built from limestone and sandstone are particularly in good condition (Figures 13 and 16), while those built from basalt require much more maintenance (four out of nine observed), which is clearly related to the irregular, often spherical shape of the rocks (Figure 14).

Table 2. Status of stone bunds in representative areas of Dogu'a Tembien in October-November 2023

Land use	Rock type used to build the stone bunds	Number of stone bunds observed	Status		
			Acceptable to perfect	Small maintenance needed	Large maintenance or rebuilding needed
Cropland	Basalt	9	5	3	1
Cropland	Sandstone or limestone	17	16	0	1
Exclosure		5	4	1	0
TOTAL		31	25	4	2

Note: exclosures in basalt areas are extremely rare, hence not included in the sample. Soils on volcanic rock are fertile, and even steep slopes are tilled or otherwise turned into eucalypt plantations.

Geomorphic effects of battlefields



Figure 17. The large Afedena enclosure [16, 52] and its surroundings were heavily affected by the three-day Ala'isa battle in late 2020, where Ethiopian and Eritrean forces jointly took on the Tigray forces [72], with, in addition to numerous battlefield deaths, a lasting environmental impact. Upper left: a long defence trench off-contour has become a rapid drainage line. Locally, the vegetation has been largely depleted. Note the bullet casings on the left rock, collected in just a few minutes. Lower left: rocks were massively taken from physical conservation structures (stone bunds) to establish combat positions. As a consequence, at right, some 7 km downstream, one of the two large checkdams for gully stabilization near Tukhul [53] that were destroyed by floods in 2021 with the accumulated sediment behind it largely washed out in 2021, 2022 and 2023. We attribute this to the strongly enhanced hydrological connectivity in the battlefield, that occupied most of the catchment. Note that even before the war, the check dams were in a critical situation, mainly because the catchment had been insufficiently protected, while check dams were already built across the river in the lower part of the catchment. The battlefield-related degradation in the catchment led to a stronger runoff response, and the check dams were washed out. Left side photos in January 2023, right hand in May 2023.



Figure 18. In Addi Qolqwal, just down from the main road, a new gully has formed. One reason are dumps from earlier road works that have narrowed the flood path. An additional cause for gullying is that stone bunds collapsed in the upper part of the gully catchment, just under the ridge, due to intense warfare. There, TDF had established an earthen antitank wall, where the Ethiopian and Eritrean armies and their tanks were blocked for a day or so. A lot of artillery was shot back and forth. Further down (lower photo), at a weak point in the landscape given the presence of vertic soil material [16, 55], the existing gully was expanded and in 2021 the floods bypassed two large check dams. Upper photo in October 2023, lower photo in May 2023.

Farmland expansion



Figure 19. A lynchet slope in Addi Qolqwal, previously under grass [43], was turned into farmland during the war period. Some rills may be discerned. Photo in October 2023.



Figure 20. At Afedena, communal rangeland has been quietly privatized by adjacent farmers; they tilled the soil gradually by hoe to evade the notice by other villagers (January 2023). Later on, during plowing, they integrated the targeted areas into their cropland and uprooted the shrubs that stood in the way. Facing hardship, and in the near absence of authorities, several farmers have expanded their farmlands in such a way at the expense of adjacent communal lands.

Peri-urban drainage



Figure 21. Effects of peri-urban drainage in the Gra Arho village: at left, many of the rocks that had been brought there in the few years before the war to pave a footpath have been dug out to strengthen the fences of the homesteads. This resulted in a narrow, incised footpath that channels rapid runoff. To the right, downslope from the village, the enhanced drainage from Gra Arho led to strong increase in gully erosion. Until 2000, there were no homesteads at all in this area. Photos in October 2023.



Figure 22. At Golab, the runoff and sediment that originate on this hillslope flood farmlands – see gravel deposits on the terraced farmland (foreground), and a stone barrage at right that the farmer made to keep the flood and its deposits out of the rest of his cropland. We investigated this hillslope in 1999-2001, when the land cover conditions were fairly the same [27]. In the following years, vegetation had regrown a little, and the slanted footpath that comes from the right was a bit better managed. Human interventions brought the landscape back to a situation unseen in the last 20 years. Grazing pressure on the slope has increased again (photo in October 2023), and, especially, a new settlement was established on the top of this structural flat after 2016, where people try to evacuate the runoff water rapidly. That runoff is then directed towards the footpath.



Figure 23. At the edge of Hagere Selam, in Maltmasha (which belongs to the adjacent village of Dingilet), a new settlement has come into existence, where the farmers have used their farmland to establish houses; the most recently established homesteads were constructed during the lawless period. Photo in October 2023.



Figure 24. Downslope from Maltmasha, the road from Dingilet to Hagere Selam is affected by gully incision (left), which originated in 2021. The footpath that runs in the thalweg on the upper side serves as a waterway during storms [50]; it is equipped with steps and check dams at regular intervals, which were not destroyed, while the floods have simply cascaded over it (right). The increased storm runoff comes in response to the establishment of the new settlement at Maltmasha. The conflict of interest is that from a management point of view the footpaths should not concentrate the runoff, yet in the village and immediately downslope, dwellers and farmers just want the footpath to concentrate the runoff and evacuate storm water as fast as possible with gullying as a consequence in downstream areas. Such situations are already difficult to manage in peace times, but during the war the community was less organized and the remaining regional and village authorities did not at all focus on spatial planning. Photos in October 2023.

Gully rehabilitation schemes



Figure 25. In a gorge at the southern side of Hagere Selam a large flood buffer dam had been constructed that got rapidly filled with coarse sediment [42], which reduced peak flows and enhanced infiltration. In the downstream area, around 1999, very active gullying occurred (Figure 26). After construction of the dam, soil conservation works and abandonment of free grazing, the gully downstream has become a linear oasis; in October 2023, there were quite some locations in the previous gully channel with ponding water. There is good grass growth, and also good discharge in the river downstream.



Figure 26. The Addi Selam gully that drains the southern part of Hagere Selam, (at left, July 1999) at the start of conservation works [21] and (at right, October 2023) after full implementation of conservation that withstood the effects of urban expansion and Tigray war. Note the strong vegetation growth in the gully and on the hillslopes at the back. The town extends on top of these hills. The dark green color of the grassy vegetation is related to the slow percolation of nutrient-rich water from the town.



Figure 27. In the Harena torrent, that drains Hagere Selam to the east, the log dams (constructed in 2011) [25] have some of their woods rotten away, but the clusters of large rocks behind them are standing strong, which leads to storm runoff that is better spread over time. The technique in itself has proven its cost effectiveness, but this is also related to the fact that the gully upstream from those check dams has been fully treated with gabion check dams. And more upstream, a large gravel dam buffers floods. There has been a maintenance campaign in places where it started to collapse – that was before the war. Inside and along the gully the vegetation is regrowing. The amount of garbage in the deposits is unprecedented and related to absence of waste collection in Hagere Selam during war and blockade.

Spring water for domestic use and irrigation



Figure 28. A dysfunctional spring development in May Toqem in November 2023. There had been several spring developments there, and the Selam Watsani project [59] built the latest chamber and taps in 2012. The taps are not working anymore, the cattle trough below it is not operational either; the water is taken directly from the overflow of the storage tank and people use it there both for livestock and domestic consumption. Already before the war it was common to see such dysfunctional or abandoned spring development projects. Additional impacts by the war and the lawless period are diverse and shown below.



Figure 29. A spring development project, installed by the May Zegzeg project [26], which transfers the spring water from Gra Arho down to the larger Harena village; it was disrupted during the war period. The project had been poorly conceived because it redirected the water from a natural spring in the Gra Arho hamlet to the large Harena village down, leaving the upland people bereft of their spring. During the war, there was lawlessness, and some people of Gra Arho broke the pipe, so their hamlet now again has access to water. Photo in October 2023.



Figure 30. In October 2023, the hand pump at Rubadera in Dingilet is working. It had not interrupted during or after the war. In this village, there are five hand pumps that are operational and that remained operational throughout the war. The water committees in this village are active in protecting the hand pumps and are also repairing them when needed. Before the war, there had been so many problems with hand pumps in general that necessitated repeated visits by experts of the Bureau of Water Resources. Now, the community was on its own, and the handpumps have been functioning for three years.



Figure 31. Bird's eye view of the Wunana valley bottom gully area [42], looking upstream (Google Earth, April 2023). Here, no successful rehabilitation had been implemented earlier on; the farmers transformed their adjacent farmlands into irrigated gardens, using water from the Abune Ayzgi spring. They started irrigating in 2018, but the irrigation activities really took off during the war; some 11 ha are now producing two harvests a year. With war and blockade, many irrigation perimeters were expanded. Wherever (seasonal) springs are available, small-scale irrigation has appeared, using gravity, treadle or motor pumps to irrigate land in valley bottoms or private gardens. All these farmer-led irrigation activities [73-76] and expansions were done without any intervention of agricultural experts. Spring discharge was good during the war period, due to sufficient rainfall; yet, interviewed farmers mention two reasons for the expansion of irrigation during the war period: (1) absence of off-farm job opportunities, so the next best option was considered to work on one's own land during the slack season, and (2) increased demand for local vegetables in the towns, as no vegetables could be imported from elsewhere in the country during the war.



Figure 32. The previous May Bi'ati gully where subsurface dams were installed in 2011 [56] has become a linear oasis, as observed in November 2023. The works led to a near-total fill of the gully (in the middle of the photo) and a raised water table; in the war period, ten farmers have done the effort to irrigate the rehabilitated gully bottom and adjacent lands.



Figure 33. At Gra Arho, an innovative farmer used a treadle pump to take water from an ephemeral river (that runs for one or two months after the end of the rainy season – right photo) through a makeshift irrigation canal (central photo) to a plot they irrigated for growing garlic (left photo). At the end of the rainy season, in September, there were no irrigation activities in their main irrigated lands down in the valley, so they could bring their treadle pump to the uplands for supplementary irrigation. As the river has fallen dry (photos in October 2023), the farmer will irrigate one more time, bringing water from the Gra Arho spring (Figure 29) by his donkey.



Figure 34. Throughout the war and blockade, the May Zahla apple tree nursery [51] has remained well fenced and guarded by the people of Dingilet. Grasses on the nursery site were harvested and sold by bidding, as an income so that guarding could continue. There has been no harrowing around the apple trees, no pruning, and the trees were watered only once in three years. Hundreds of apple trees were growing in October 2023, generally with small leaves. A few apple trees perished in the upper area where it is driest. May Zahla is a naturally moist place, so that apple trees could survive. Also, the rootstock reproduction site was in good shape, so trees could be harvested after the nursery restarts, and sold again to the farmers. There was no evidence of wood harvesting or grazing in the nursery. It was well protected, though not managed, as there were no salaries. People know the benefit of this nursery for their income and for their village. With committed coordination and manual labour, the nursery can be restarted rapidly.



Figure 35. In the village of Dingilet, irrigated vegetable production has continued at many homesteads throughout the war period (November 2023).



Figure 36. Several farmers in Dingilet have an apple tree production site in their garden, which is part of a project jointly with the nursery. The nursery activities had stopped but the young trees have continued growing in their garden. People from as far as Aksum now come straight to Dingilet to purchase young, grafted apple trees. One reason is that the highly subsidized import of seedlings from Chench (South Ethiopia) was disrupted by the war, and apple trees can only be purchased locally, at market conditions. Photo in October 2023.



Figure 37. In May Sa'iri, the Shafa Hambar spring (located at the upper right of the left photo) is channeled to many homesteads by a 600 m long cemented canal. Among several irrigated gardens, there is a larger private cooperative vegetable garden (at left, October 2023) in which three relatives grow garlic, tomato, Swiss chard and green pepper (at right, February 2024). By habit, the farmers expect the government to provide seeds for irrigated vegetables. During the war period, some farmers were producing garlic seed which they sold to other farmers at the price of 180 ETB for a “cup” of standardized dimension (i.e. the lid of a jerrycan, 0.055 L). Farmers often multiply carrot seeds themselves. Tomato, chard and green pepper seeds are bought at approx. 70 birr per cup. The cooperative garden continued its activities throughout the war period, because it was deemed a safe place, away from roads.

Summarizing photograph: an example of land resilience



Figure 38. Landscape on limestone at Igri Mallow in October 2023. Stone bunds were established along the contour some 20 years ago and are intact; patches with shallow soils are communal land part of the Igri Mallow enclosure [39, 40], where no wood harvesting occurred during the war. At the centre of the photo, the village of Hech'i with traditional agroforestry on farm boundaries [77]. According to the local farmers, “you have to grow trees on your own farmland boundaries if you wish to cope with the shortage of firewood”.

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References

1. World Future Council. *Tigray Gold Award*. <https://www.worldfuturecouncil.org/p/2017-desertification/>. 2017.
2. Annys, S., et al., *Tigray: atlas of the humanitarian situation*. <https://zenodo.org/record/5807266>. 2021.
3. Tesfaalem Ghebreyohannes, et al., *Challenges and resilience of an indigenous farming system during wartime (Tigray, north Ethiopia)*. *Agronomy for Sustainable Development*, 2022. **42**.
4. von Carnap, T., et al., *Using satellite imagery to monitor remote rural economies at high frequency*. arXiv preprint arXiv:2407.12953, 2024.
5. Nyssen, J., et al., *Tigray's wartime landscape – a regional geographical study in the Tembien highlands*. 2023, Mekelle University & Ghent University: Mekelle, Tigray, Ethiopia & Ghent, Belgium.
6. Weldemichel, T.G., *Inventing hell: how the Ethiopian and Eritrean regimes produced famine in Tigray*. *Human Geography*, 2021. **0**(0): p. 19427786211061431.
7. Plaut, M., *The Tigray Famine*. *The RUSI Journal*, 2021. **166**(4): p. 22-28.
8. Emnet Negash, et al., *Remote sensing reveals how armed conflict regressed woody vegetation cover and ecosystem restoration efforts in Tigray (Ethiopia)*. *Science of Remote Sensing*, 2023. **8**: p. 100108.
9. Solomon Hishe, et al., *The impacts of armed conflict on vegetation cover degradation in Tigray, northern Ethiopia*. *International Soil and Water Conservation Research*, 2023.
10. Nyssen, J., et al., *Effects of land use and land cover on sheet and rill erosion rates in the Tigray Highlands, Ethiopia*. *Zeitschrift für Geomorphologie*, 2009. **53**: p. 171-197.
11. Frankl, A., et al., *Factors controlling the morphology and volume (V)–length (L) relations of permanent gullies in the Northern Ethiopian Highlands*. *Earth Surface Processes and Landforms*, 2013. **38**(14): p. 1672-1684.
12. Moeyersons, J., et al., *Mass movement mapping for geomorphological understanding and sustainable development: Tigray, Ethiopia*. *Catena*, 2008. **75**(1): p. 45-54.
13. Nyssen, J., et al., *The environmental significance of the remobilisation of ancient mass movements in the Atbara-Tekeze headwaters, Northern Ethiopia*. *Geomorphology*, 2003. **49**(3-4): p. 303-322.
14. Nyssen, J., et al., *Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years*. *Science of The Total Environment*, 2014. **485-486**: p. 164-179.
15. Nyssen, J., et al., *Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia*. *Soil and Tillage Research*, 2007. **94**(1): p. 151-163.
16. Etefa Guyassa, et al., *Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia*. *Journal of Hydrology*, 2017. **545**: p. 299-309.
17. Aerts, R., J. Nyssen, and Mitiku Haile, *On the difference between "exclosures" and "enclosures" in ecology and the environment*. *Journal of Arid Environments*, 2009. **73**: p. 762-763.
18. Nyssen, J., et al., *Impact of soil and water conservation on catchment hydrological response – a case in northern Ethiopia*. *Hydrological Processes*, 2010. **24**(13): p. 1880-1895.
19. Fikir Alemayehu, et al., *The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia)*. *Resources, Conservation and Recycling*, 2009. **53**: p. 192-198.
20. Nyssen, J., et al., *Crop Cultivation at Wartime – Plight and Resilience of Tigray's Agrarian Society (North Ethiopia)*. *Defence and Peace Economics*, 2023. **34**(5): p. 618-645.

21. Nyssen, J., et al., *The effectiveness of loose rock check dams for gully control in Tigray, Northern Ethiopia*. Soil Use and Management, 2004. **20**: p. 55-64.
22. Vancampenhout, K., et al., *Stone bunds for soil conservation in the northern Ethiopian highlands: Impacts on soil fertility and crop yield*. Soil and Tillage Research, 2006. **90**(1-2): p. 1-15.
23. Desta Gebremichael, et al., *Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray highlands, Northern Ethiopia*. Soil Use Manag. , 2005. **21**: p. 287-297.
24. Nyssen, J., et al., *Soil and water conservation in Tigray (Northern Ethiopia): the traditional daget technique and its integration with introduced techniques*. Land Degradation and Development, 2000. **11**: p. 199-208.
25. Nyssen, J., et al., *Boulder-faced Log Dams as an Alternative for Gabion Check Dams in First-order Ephemeral Streams with Coarse Bed Load in Ethiopia*. Journal of Hydraulic Engineering, 2017. **143**(1): p. 05016005
26. Amanuel Hadera and J. Nyssen, *The Integrated May Zeg-Zeg Watershed Management Project. Project proposal submitted to Trocaire*. 2003, Ethiopian Catholic Church Social and Development Commission of Adigrat and Mekelle University: Mekelle, Ethiopia.
27. Nyssen, J., et al., *Processes and rates of rock fragment displacement on cliffs and scree slopes in an amba landscape, Ethiopia*. Geomorphology, 2006. **81**(3-4): p. 265-275.
28. Nyssen, J., et al., *Assessment of gully erosion rates through interviews and measurements: a case study from Northern Ethiopia*. Earth Surf. Proc. Landf., 2006. **31**: p. 167-185.
29. Nyssen, J., et al., *Understanding spatial patterns of soils for sustainable agriculture in northern Ethiopia's tropical mountains*. PloS one, 2019. **14**(10): p. e0224041.
30. Nyssen, J., et al., *How soil conservation affects the catchment sediment budget - a comprehensive study in the north Ethiopian highlands*. Earth Surface Processes and Landforms, 2009. **34**: p. 1216-1233.
31. Nyssen, J., et al., *Dynamics of soil erosion rates and controlling factors in the Northern Ethiopian Highlands - towards a sediment budget*. Earth Surface Processes and Landforms, 2007. **33**(5): p. 695-711.
32. Nyssen, J., et al., *Soils and land use in the Tigray highlands (Northern Ethiopia)*. Land Degradation & Development, 2008. **19**(3): p. 257-274.
33. Nyssen, J., et al., *Spatial distribution of rock fragments in cultivated soils in northern Ethiopia as affected by lateral and vertical displacement processes*. Geomorphology, 2002. **43**(1-2): p. 1-16.
34. Vandecasteele, I., et al., *Hydrogeology and groundwater flow in a basalt-capped Mesozoic sedimentary series of the Ethiopian highlands*. Hydrogeology journal, 2011. **19**(3): p. 641-650.
35. Walraevens, K., et al., *Groundwater recharge and flow in a small mountain catchment in Northern Ethiopia*. Hydrological Sciences Journal, 2009. **54**: p. 739-753.
36. Lanckriet, S., et al., *A political ecology perspective of land degradation in the North Ethiopian Highlands*. Land Degrad. Develop., 2015. **26**(5): p. 521-530.
37. Deckers, J., et al., *Understanding Soil Spatial Patterns for Sustainable Development*, in *Geotrekking in Ethiopia's Tropical Mountains*, J. Nyssen, M. Jacob, and A. Frankl, Editors. 2019, Springer Nature: Cham (CH). p. 361-372.
38. Nyssen, J., *Vegetation and soil erosion in Dega Tembien (Tigray, Ethiopia)*. Bulletin du Jardin botanique national de Belgique/Bulletin van de Nationale Plantentuin van België, 1997: p. 39-62.
39. Etefa Guyassa, et al., *From runoff contributor to runoff absorber: Spate irrigation on exclosures in Tigray's semi-arid environment (Ethiopia)*. Ecohydrology, 2023. **16**(1): p. e2480.
40. Descheemaeker, K., et al., *Changes in water flows and water productivity upon vegetation regeneration on degraded hillslopes in northern Ethiopia: a water balance modelling exercise*. The Rangeland Journal 2009. **31**: p. 237-249.

41. Amanuel Zenebe, et al., *Land use and suitability for rainfed agriculture*, in *Geo-trekking in Ethiopia's tropical mountains*. 2019, Springer. p. 373-386.
42. Nyssen, J., *Description of trekking routes in Dogu'a Tembien*, in *Geo-Trekking in Ethiopia's Tropical Mountains, the Dogu'a Tembien District*, J. Nyssen, M. Jacob, and A. Frankl, Editors. 2019, SpringerNature: Cham (CH). p. 557-675.
43. Lannoeye, W., et al., *The use of SfM-photogrammetry to quantify and understand gully degradation at the temporal scale of rainfall events: an example from the Ethiopian drylands*. *Physical Geography*, 2016. **37**(6): p. 430-451.
44. Meheretu, Y., et al., *Rodent abundance, stone bund density and its effects on crop damage in the Tigray highlands, Ethiopia*. *Crop Protection*, 2014. **55**(0): p. 61-67.
45. Nyssen, J., M. Jacob, and A. Frankl, *Geo-Trekking in Ethiopia's Tropical Mountains, the Dogu'a Tembien District*. Springer GeoGuide. 2019, Heidelberg (Germany): Springer Nature. xxxiv + 675.
46. Jacob, M., et al., *Dogu'a Tembien's Tropical Mountain Climate*, in *Geo-trekking in Ethiopia's Tropical Mountains*. 2019, Springer. p. 45-61.
47. Descheemaeker, K., et al., *Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia*. *Journal of Hydrology*, 2006. **331**(1-2): p. 219-241.
48. Descheemaeker, K., et al., *Two rapid appraisals of FAO-56 crop coefficients for semiarid natural vegetation of the northern Ethiopian highlands*. *Journal of Arid Environments*, 2011. **75**(4): p. 353-359.
49. Nyssen, J., et al., *Impact of road building on gully erosion risk: a case study from the Northern Ethiopian Highlands*. *Earth Surface Processes and Landforms*, 2002. **27**(12): p. 1267-1283.
50. Nyssen, J., *Soil erosion in the Tigray highlands (Ethiopia). II. Soil loss estimation*. *Geo-Eco-Trop*, 1997(21): p. 27-49.
51. Dereje Ashebir, et al., *Growing apple (Malus domestica) under tropical mountain climate conditions in northern Ethiopia*. *Experimental Agriculture*, 2010. **46**(1): p. 53-65.
52. Wolde Mekuria, et al., *Effectiveness of exclosures to control soil erosion and local community perception on soil erosion in Tigray, Ethiopia*. *African Journal of Agricultural Research*, 2009. **4**(4): p. 365-377.
53. Frankl, A., et al., *Gully Erosion and Control in the Tembien Highlands*, in *Geo-trekking in Ethiopia's Tropical Mountains: The Dogu'a Tembien District*, J. Nyssen, M. Jacob, and A. Frankl, Editors. 2019, Springer International Publishing: Cham. p. 333-343.
54. Moens, T., M. Jacob, and S. Lanckriet, *Boswellia Incense in the Giba River Gorge*. *Geo-trekking in Ethiopia's Tropical Mountains: The Dogu'a Tembien District*, 2019: p. 293-300.
55. Frankl, A., et al., *Detailed recording of gully morphology in 3D through image-based modelling*. *Catena*, 2015. **127**: p. 92-101.
56. Frankl, A., et al., *Integrated solutions for combating gully erosion in areas prone to soil piping: innovations from the drylands of Northern Ethiopia*. *Land Degradation & Development*, 2016. **27**: p. 1797-1804.
57. Lanckriet, S., et al., *Gully cut-and-fill cycles as related to agro-management: a historical curve number simulation in the Tigray Highlands*. *Earth Surface Processes and Landforms*, 2015. **40**(6): p. 796-808.
58. Van de Wauw, J., et al., *Soil-landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia*. *Catena*, 2008. **75**: p. 117-127.
59. Frankl, A., et al., *Implementing improved sanitation facilities and drinking water supplies from an environmentally sound approach: the SELAM WATSANI project in the hinterland of Mekelle University*, in *GAPSYM10*. 2016, Ghent Africa Platform: Ghent, Belgium. p. 27-28.
60. WeForest, *Combating desertification in northern Ethiopia. Report, 5 p.* . 2017, WeForest: Brussels. p. 5.
61. Moeyersons, J., et al., *On the origin of rock fragment mulches on Vertisols: A case study from the Ethiopian highlands*. *Geomorphology*, 2006. **76**(3-4): p. 411-429.

62. Nyssen, J., J. Poesen, and J. Deckers, *Land degradation and soil and water conservation in tropical highlands*. Soil and Tillage Research, 2009. **103**: p. 197-202.
63. Nyssen, J., et al., *Environmental change, geomorphic processes and land degradation in tropical highlands*. Catena, 2008. **75**(1): p. 1-4.
64. Van Passel, J., W. De Keersmaecker, and B. Somers, *Monitoring Woody Cover Dynamics in Tropical Dry Forest Ecosystems Using Sentinel-2 Satellite Imagery*. Remote Sensing, 2020. **12**(8): p. 1276.
65. Lanckriet, S., et al. *EthioTrees: ecosystem service valuation in the Tembien Highlands (North Ethiopia)*. in *10th Symposium of Ghent Africa Platform (GAPSYM-10): Celebrating partnership with Africa: demonstrating the value of international collaboration on teaching and research*. 2016.
66. Sebsebe Demissew, *A Central American weedy Salvia in Ethiopia*. Lamiales Newsletter, 1996. **4**: p. 3-4.
67. GBIF. *Salvia tiliifolia*, occurrence map. https://www.gbif.org/occurrence/map?taxon_key=2927066. 2024.
68. Nyssen, J., et al., *Land management in the northern Ethiopian highlands: local and global perspectives; past, present and future*. Land Degradation & Development, 2015. **26**(7): p. 759-764.
69. Jacob, M., et al., *Land cover dynamics in the Simien Mountains (Ethiopia), half a century after establishment of the National Park*. Regional environmental change, 2017. **17**(3): p. 777-787.
70. Cronin, M., et al., *Local agro-ecological knowledge of sustainable intensification of the tree-crop-livestock system in the Ethiopian Highlands, Endamahoni Woreda, Tigray Region*. 2013, Addis Ababa: International Livestock Research Institute.
71. Grant, S., *A Study on the Livestock Population and the Forage Resource in the Nazareth Fuelwood Project area, (Yererand Kereyu Awraja), Eastern Shewa Administrative Region, including a proposal for a silvo pastoral approach within the Fuelwood Plantation*. 1989, Addis Abeba: United Nations Sudan-Sahelian Office.
72. Nyssen, J., *Repeat photography of a joint military operation involving the Ethiopian and Eritrean armies in Inderta, Tigray, Ethiopia (November 2020) [Data set]*, Zenodo, Editor. 2023.
73. Passarelli, S., et al., *Evaluating the pathways from small-scale irrigation to dietary diversity: evidence from Ethiopia and Tanzania*. Food Security, 2018. **10**(4): p. 981-997.
74. Burney, J.A. and R.L. Naylor, *Smallholder irrigation as a poverty alleviation tool in sub-Saharan Africa*. World Development, 2012. **40**(1): p. 110-123.
75. De Bont, C., et al., *Modernisation and African farmer-led irrigation development: ideology, policies and practices*. Water Alternatives, 2019. **12**(1): p. 107-128.
76. Kashi Kafle, et al., *Who is likely to benefit from public and private sector investments in farmer-led irrigation development? Evidence from Ethiopia*. The Journal of Development Studies, 2022. **58**(1): p. 55-75.
77. Berihu Tesfamariam, et al., *Agroforestry practices for climate change adaptation and livelihood resilience in drylands of Ethiopia*. Forest Science and Technology, 2023: p. 1-11.