Rehabilitating degraded landscapes through area exclosure: Effects on vegetation recovery and livelihoods in eastern Tigray, Ethiopia

Araya Kiros[1] Hailemariam Meaza*[2] Biadgilgn Demissie[2]

Abstract

Area exclosure has been a key environmental rehabilitation strategy in northern Ethiopia since 1991. It aimed at restoring degraded watersheds. In 2006, the Millennium Village Project initiated large-scale environmental rehabilitation, using area exclosures in Koraro village, Eastern Tigray. This study examined the contribution of area exclosures to vegetation cover recovery and the livelihoods of local farmers. Historical land use/land cover dynamics were analyzed using satellite imagery from Landsat 4-5 Thematic Mapper (TM) for the years 1984, 1995, 2000, and 2010, and Landsat 8 for 2014. Changes in vegetation cover were assessed using the Normalized Difference Vegetation Index (NDVI). In addition, household surveys and key informant interviews were conducted to evaluate the livelihood impacts of area exclosures. Over the past 30 years, the dominant land use/land cover types in the study area have included farmland, settlement, shrubland, and Bareland. NDVI analysis revealed a marked increase in vegetation cover from 2010 to 2014, indicating the positive impact of area exclosures. Furthermore, the study found that crop yields on farmlands adjacent to area exclosures were 2.2 times higher than those near open, non-enclosed grazing areas. However, the strict "remove livestock from grazing areas" principle presents a challenge to the wider acceptance and sustainability of exclosure practices among local communities. Area exclosures have significantly enhanced vegetation recovery and improved the livelihoods of smallholder farmers in the study area. We recommend that area exclosure practices be scaled up across other dryland regions, with greater emphasis on participatory implementation and locally adapted management approaches to ensure long-term success.

Keywords: land degradation, area exclosure, livelihood resources, NDVI, northern Ethiopia

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Introduction

Land resources provide essential ecosystem services and underpin the livelihoods of rural communities, particularly in developing countries (Ahmadi et al., 2010). However, natural resources across the globe are under increasing threat, with an estimated 20% of cultivated lands, 30% of forests, and 10% of grasslands degraded (FAO 2008). This degradation is most severe in tropical countries, where intensified economic activities accelerate the loss of ecosystem functionality (Lambin et al., 2003; Seto et al., 2002). In the northern highlands, land degradation remains a major environmental concern (Nyssen et al., 2004; Nyssen et al., 2009), exacerbated by poverty, steep topography, erratic rainfall, and limited vegetation cover.

Forest depletion is particularly acute in northern Ethiopia, where deforestation due to agricultural expansion, fuelwood collection, and construction demands continues at an alarming rate (Taddese, 2001; Babulo et al., 2008). Once believed to be 40% forested, Ethiopia's forest cover had reportedly declined to 2.4% in 1990 (Friis, 1986), although recent estimates suggest a recovery to 15.7% (World Bank, 2020). In the Tigray region, forest resources remain fragmented, and the combined effects of deforestation and soil erosion have reduced ecosystem services, deepening poverty and food insecurity for smallholder farmers (Babulo et al., 2008; Mekuria et al., 2017).

Recognizing the urgency of reversing land degradation, government and non-governmental organizations-initiated land rehabilitation programs as early as the 1970s (Campbell, 1991; Hoben, 1995). Since the 1990s, the Tigray Region has pursued large-scale environmental restoration through integrated watershed management and community-based mobilization approaches, such as the "be like bees" campaign (Segers et al., 2009). Among these interventions, area exclosures—land areas protected from human and livestock interference to promote natural regeneration—have become a cornerstone of landscape rehabilitation (Haile & Gebrehiwot, 2001; Lemenih & Kassa, 2014; Mekuria et al., 2007).

One notable initiative is the Millennium Village Project (MVP), launched in 2006 in Koraro Tabia, Hawzen district, Eastern Tigray, one of the most degraded and food-insecure areas. In collaboration with the World Food Program and local authorities, MVP promoted area exclosures and reforestation as part of its strategy to combat hunger and restore ecosystems. These exclosures not only aimed to improve vegetation cover but also to enhance farmers' livelihoods by restoring degraded lands (Descheemaeker et al., 2006; Nyberg et al., 2019; Yirdaw & Monge, 2018). Several studies report the ecological success of exclosures in improving vegetation density, biodiversity, and ecosystem services (Mekuria & Aynekulu, 2013; Yimer et al., 2015; Nyssen et al., 2014). However, some have also noted setbacks, such as the decline in vegetation cover after project phase-outs (Gebregergs et al., 2021).

Remote sensing technologies, particularly satellite imagery such as Landsat, have emerged as vital tools for monitoring land use and vegetation dynamics over time and space. Landsat's long historical archive and moderate spatial resolution enable the detection of vegetation cover changes in data-scarce regions (Melesse et al., 2007). These technologies allow researchers to assess the biophysical impact of land rehabilitation projects like area exclosures, offering cost-effective and repeatable assessments at different scales. Yet, despite their potential, many previous studies in Ethiopia have primarily relied on field-based methods, often neglecting the integration of remote sensing data with local socioeconomic insights.

This study addresses these gaps by examining the impact of area exclosures on vegetation cover and local livelihoods in the Koraro Tabia using Landsat imagery and household survey data. Specifically, it aims to: (1) investigate the trend of land use/land cover change in the Koraro Tabia; (2) compare the vegetation cover between exclosures and adjacent open areas; and (3) assess the contribution of exclosures to the livelihoods of poor farmers. By aligning with the Sustainable Development Goals, this study offers valuable feedback to donors, implementers, and policymakers on enhancing land investment strategies in the drylands. It also contributes to the scientific literature by demonstrating how remote sensing technologies, coupled with local knowledge, can support sustainable land management.

Methods and Materials

The study area

The study area is located in the eastern zone of Tigray Regional State of Northern Ethiopia (Figure 1). It is located in the Tekeze headwater. It is situated about 27 km southwest of Hawzen Town. The geographical location of the area is between $13^0$47'35"N to $13^0$55'47"N latitudes and $39^0$11'40"E to $39^0$17'55"E longitudes.

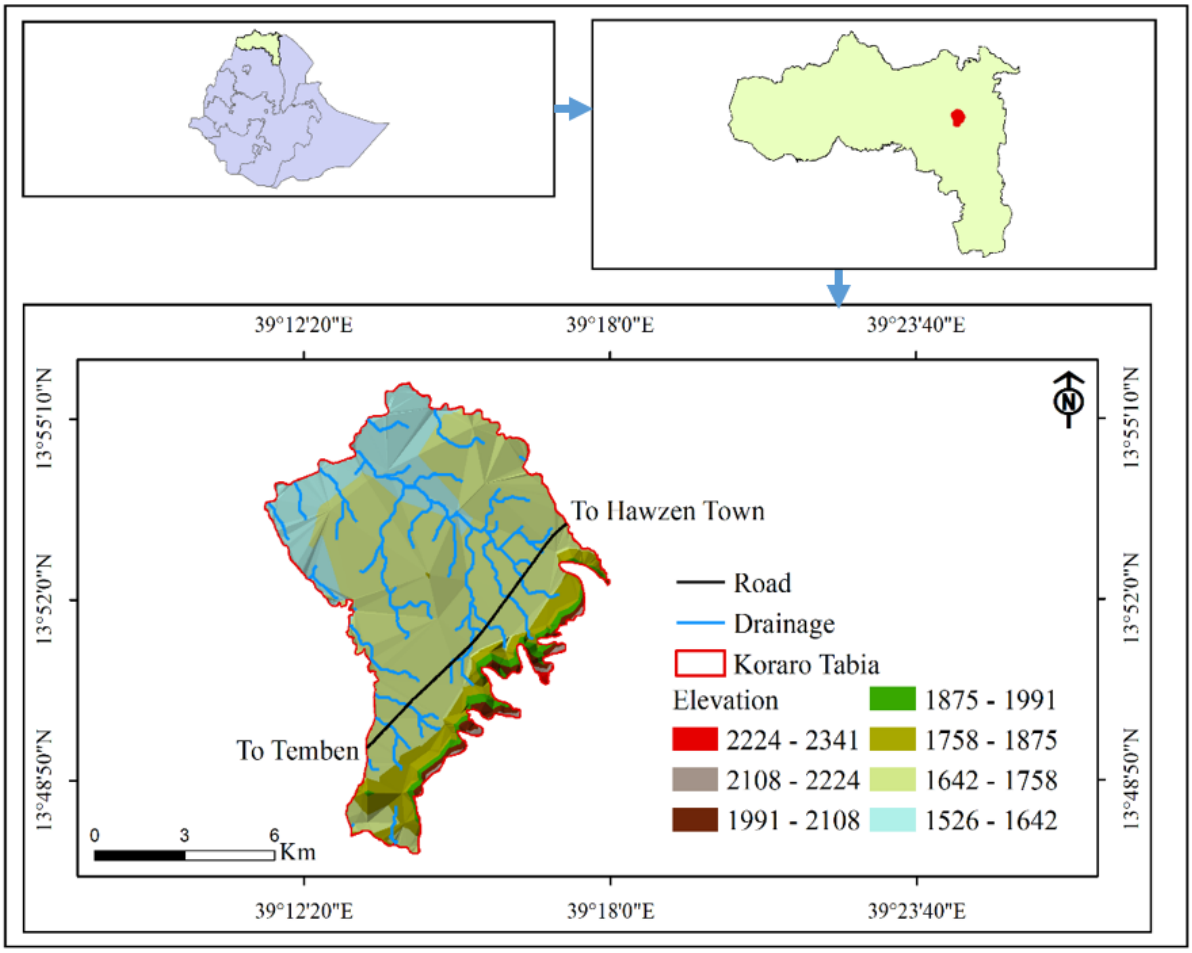

Figure 1. Map of the study area.

The study area, located in eastern Tigray, is characterized by diverse topographic features, including rugged escarpments to the southeast and east, and expansive, dusty semi-arid lowlands toward the west and northwest. Elevation in the study village ranges from approximately 1,526 meters above sea level at Agefet and along the *Werie* River to 2,341 meters at the peak of *Abune Gerecheal Mountain* (Figure 1).

Climatically, the area falls within the Weyna Dega agroecological zone, which is typified by moderate elevation and semi-arid conditions (Kahsay et al., 2019). Daily temperatures fluctuate between 14.5°C and 20.5°C. The average annual rainfall is relatively low, at 548.5 mm, resulting in recurrent hydrological deficits during most months of the year. The study area exhibits a dendritic drainage network, with seasonal rivers such as *Siglti* and its tributaries flowing predominantly from the southeast to the northwest (Figure 1).

Agriculture is the principal livelihood activity, dominated by the cultivation of staple crops, including finger millet (Eleusine coracana L.), wheat (Triticum aestivum L.), maize (Zea mays L.), barley (Hordeum vulgare L.), and teff (Eragrostis teff). Despite the degraded terrain and steep slopes, smallholder farmers continue to engage in rainfed subsistence farming using traditional ploughing methods (Meaza et al. 2016). Livestock husbandry is also widely practiced, with households rearing cattle, sheep, goats, donkeys, poultry, and honeybees. However, the productivity of agricultural systems remains constrained by ongoing land degradation, declining soil fertility, scarcity of arable land, and limited access to communal grazing areas.

Methods

Data and sources of data

To analyze the trends in land use/land cover and vegetation cover change, both primary and secondary data sources were utilized. Primary data were gathered through repeat field observations, in-depth interviews, and a structured questionnaire administered to local farmers and agricultural experts. Secondary data were derived from freely available satellite imagery, including Landsat series, as well as published and unpublished reports from governmental and non-governmental organizations to complement the primary data.

In line with Hussien et al. (2018), socioeconomic data were also collected to contextualize the trends in land use/cover dynamics, assess vegetation changes, and evaluate the impacts of area exclosures on local livelihoods. The use of repeated field observations and interviews enabled a deeper understanding of biophysical and social transformations in the landscape.

Topographic information was generated using the ASTER Global Digital Elevation Model (30m × 30m resolution), processed with ArcGIS 10 software to produce a detailed elevation map of the study area. These spatial datasets, combined with socioeconomic information, facilitated a comprehensive analysis of the environmental and livelihood outcomes associated with area exclosure practices in Eastern Tigray.

Satellite image acquisition and preprocessing

To analyze land use/land cover, multi-temporal satellite imagery was acquired from the USGS Earth Explorer portal (https://earthexplorer.usgs.gov/). Specifically, Landsat 4-5 Thematic Mapper (TM) imagery for the years 1984, 1995, 2000, and 2010, and Landsat 8 Operational Land Imager (OLI) imagery for 2014 were used for the analysis (Table 1).

Table 1. Types of satellites with their acquisition data

Satellite	Date of acquisition	Path and row	Resolution
Landsat 4-5 TM	25/05/1984	169/50	30 m x 30 m
Landsat 4-5 TM	27/04/1995	169/50	30 m x 30 m
Landsat 4-5 TM	10/05/2000	169/50	30 m x 30 m
Landsat 4-5 TM	14/01/2010	169/50	30 m x 30 m
Landsat 8 TIRS	26/02/2014	169/50	30 m x 30 m

Since satellite imagery of the study area was unavailable prior to 1984 along Path 169 and Row 50; the analysis begins from the year 1984. The selected Landsat images were captured in different months and on varying dates, depending on cloud cover conditions and data availability (Table 1). In line with Campbell (2002), these satellite images were used to examine both historical and recent trends in land use/land cover change.

The images were downloaded from the USGS Earth Explorer website and processed using ERDAS Imagine 2010 software. Initial preprocessing of land sat images included layer stacking (band combination), followed by radiometric and geometric corrections to enhance image quality and spatial accuracy. Subsequently, the images were clipped to the boundary of the study area using a shapefile and the "Subset and Chip" tool in ERDAS Imagine, in preparation for classification and further analysis.

Sample size and sampling procedure

Ground Control Points (GCPs) were collected through repeated field surveys to support the analysis of land use/land cover and vegetation cover change. A total of 120 GCPs, 30 for each land cover class, were gathered for validation during the classification process. These points were strategically sampled from both area exclosure and adjacent non-exclosure sites to enable the detection of variations in NDVI values and assess vegetation recovery.

To complement the spatial analysis, household-level data were collected using interviews and questionnaire. Out of 40 households located near the area exclosures, 25 were randomly selected using a lottery method. In addition, five agricultural experts were purposively selected for in-depth interviews based on their professional experience and relevance to the study area.

Data analysis

Image classification: Supervised classification was applied to categorize and analyze the recent land use/land cover of the study area. This method involves the identification of homogeneous sample sites—referred to as training areas—for each land cover class, which are then used to guide the classification process (Lillesand et al., 2004). The selection of an appropriate classification algorithm was based on the spectral properties of these training areas.

Training samples with similar reflectance values were defined and collected using the Signature Editor tool in ERDAS Imagine 2010. Polygons were manually digitized over representative areas of each land cover class. The spectral signatures generated from these polygons were used to classify individual pixels throughout the image. The classification process continued until all pixels were assigned to one of the defined classes. The Maximum Likelihood Classifier (MLC)—a widely used parametric algorithm—was employed to assign pixels based on the statistical probability of class membership (Jensen, 2005).

Following the FAO (2016) land use/land cover classification scheme, satellite images were classified into four major categories: shrubland, bareland, farmland, and settlement, using ERDAS Imagine 2010 and ArcGIS 10 software (Table 2).

Accuracy assessment: An accuracy assessment was conducted to determine how well the classified land use/cover maps matched the actual conditions on the ground. This validation was performed for the years 1984, 1995, 2000, 2010, and 2014, using satellite imagery from Landsat 4-5 TM (1984–2010) and Landsat 8 OLI (2014), along with corresponding ground truth points collected for each land cover class.

The results showed that the overall classification accuracy exceeded 80% for each year, which is within acceptable limits for land use/cover studies and indicates a high level of reliability.

Land use/cover change detection: Land use/land cover change analysis was carried out through pixel-by-pixel comparison of the classified Landsat images using matrix union analysis. This technique generates a change matrix, which provides detailed information about how much area from one land cover class transitioned to another between different time periods. The approach effectively captures the spatiotemporal dynamics of land transformation.

NDVI calculation: The Normalized Difference Vegetation Index (NDVI) was used to assess changes in vegetation cover over the last 30 years. NDVI is a widely applied remote sensing technique used to monitor the density and health of vegetation, as well as photosynthetic activity, over time (Ghorbani et al., 2012; Seaquist et al., 2002).

NDVI values range from -1.0 to +1.0, where higher positive values indicate healthy green vegetation, values near zero represent bare soil or rock, and negative values typically correspond to water bodies or cloud cover (Lillesand & Kiefer, 2000; 2004). According to Jensen (1996), NDVI is calculated using the following equation:

$$\text{NDVI} = \frac{(\text{NIR}-\text{R})}{(\text{NIR}+\text{R})}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where:
NIR *=Near-Infrared Reflectance*
R *= Red Band Reflectance*

This index enabled the detection of spatiotemporal vegetation changes, particularly the effectiveness of area exclosures in improving vegetation cover in the study area.

Socioeconomic data analysis: Quantitative socioeconomic data were analyzed using descriptive statistics to address the research questions concerning the impact of area exclosures on farmers' livelihoods. The qualitative data obtained through interviews and field observations were thematically organized and narratively analyzed to complement and enrich the quantitative findings.

Results

Temporal distribution of land cover

Table 2 and Figure 2 illustrate the temporal trends in land use/land cover change in the study area from 1984 to 2014. In 1984, farmland was the dominant land cover type, accounting for approximately 53% of the total area, followed by bareland, which constituted around 27%. By 1995, farmland remained the most extensive land cover class, although its proportion slightly declined to 49%. Notably, shrubland became the second most dominant class in 1995, increasing to 27%, while the proportion of bareland decreased sharply to 9%.

This shift indicates a general decline in both farmland and bareland between 1984 and 1995, accompanied by a noticeable increase in shrubland and settlement areas. In 2000, shrubland covered approximately 1,050.21 hectares, representing 12.8% of the study area, whereas farmland expanded to 56.2%, indicating a recovery in agricultural land use during that period.

In 2010, shrubland further increased to 15.8%, while farmland declined slightly to 52%. Compared to 2000, bareland and farmland both exhibited a reduction in area, whereas shrubland and settlement areas showed an upward trend. By 2014, the extent of shrubland had grown to 17% of the total land area, suggesting continued vegetation recovery, possibly influenced by area exclosure practices. These findings reflect dynamic land use transitions over the 30 years, with a consistent pattern of increasing shrubland and settlement areas, and fluctuating trends in farmland and bareland.

Table 2. Summary statistics of land use and land cover from 1984 to 2014

Class Name	**Year**									
	1984 (ha)	%	1995 (ha)	%	2000 (ha)	%	2010 (ha)	%	2014 (ha)	%
Shrubland	649.53	8	2220.4	27	1050.21	12.8	1297.61	15.8	1396.26	17
Farmland	4348. 71	53	4044.8	49	4620.96	56.2	4243.06	51.56	3866.67	47
Settlement	1010.07	12	1261.17	15	1929.6	23.4	2279.25	27.7	2442.42	30
Bare land	2218.77	27	700.29	9	626.31	7.6	407.16	4.94	521.73	6
Total	8227.08	100	8227.08	100	8227.08	100	8227.08	100	8227.08	100

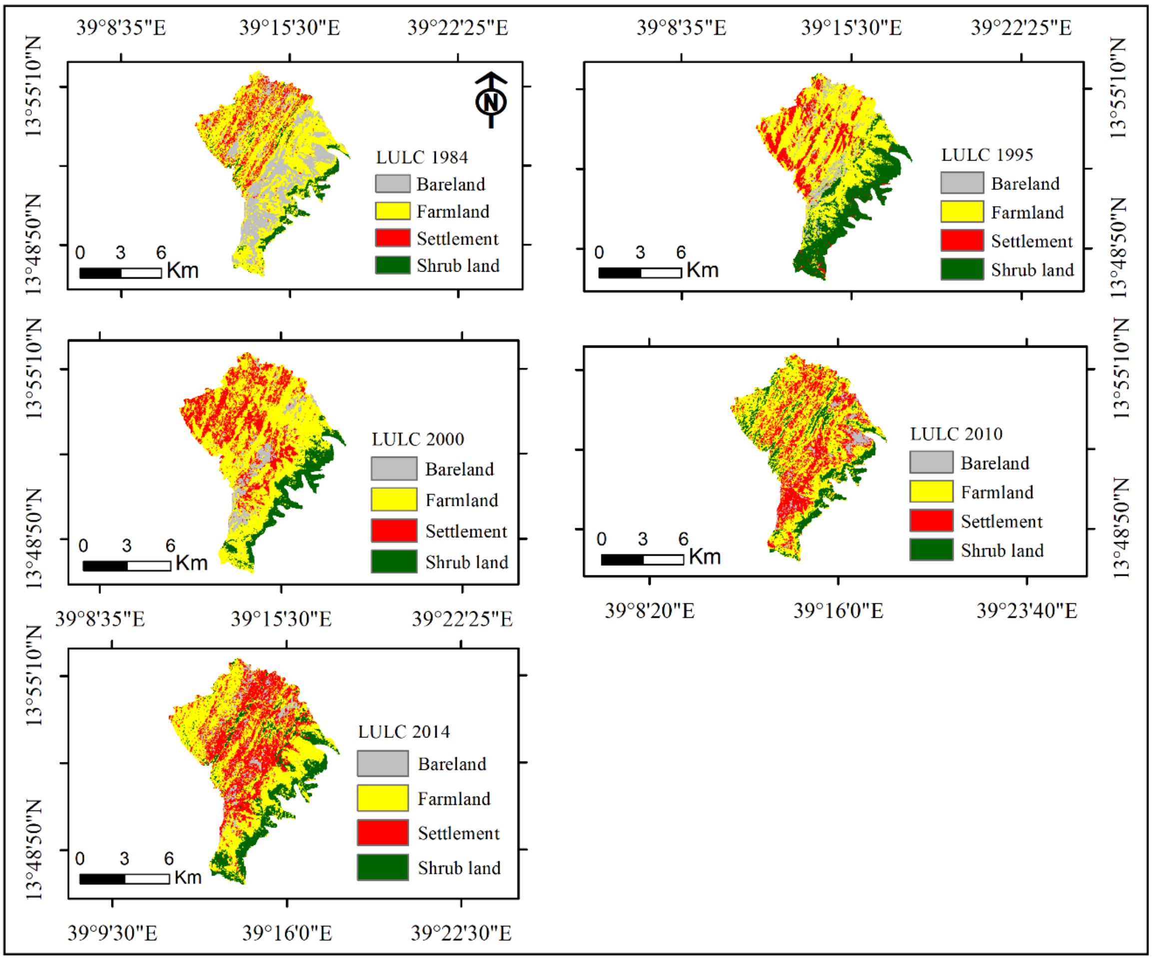

Figure 2. Land use/cover map of Koraro in 1984, 1995, 2000, and 2014.

Land cover change from 1984 to 2014

The study indicates that there has been a massive change of farmland (2053.08 ha) into settlement, shrubland, and bareland from 1984 to 1995 (Table 3). Indeed, Table 3 shows that the size of farmland and bareland was the major land cover change observed from 1984 to 1995.

Table 3. Land use land cover change matrix between 1984 and 2014

	1984					
	Class Name	Shrubland	Farmland	Settlement	Bareland	Total
1995	Shrubland	474.93	1080.27	2.34	663.3	2220.84
	Farmland	22.05	2295.63	669.51	1057.59	4044.78
	Settlement	152.55	903.78	184.5	20.34	1261.17
	Bareland	0	69.03	153.72	477.54	700.29
	Class Total	649.53	4348.71	1010.07	2218.77	8227.08
	Class change	174.6	2053.08	825.53	1741.23	4794.44
	1995					
2000	Shrubland	990	27	33.12	0.09	1050.21
	Farmland	1132.29	2189.7	1104.84	194.13	4620.96
	Settlement	27.54	1604.16	119.61	178.29	1929.6
	Bareland	71.01	223.92	3.6	327.78	626.31
	Total	2220.84	4044.78	1261.17	700.29	8227.08
	Class change	1230.84	1855.08	1141.56	372.51	4599.99
	2000					
2010	Shrubland	549	661.86	86.76	0	1297.62
	Farmland	396.81	2596.14	1150.47	99.63	4243.05
	Settlement	65.7	1172.16	672.66	368.73	2279.25
	Bareland	38.7	190.8	19.71	157.95	407.16
	Class total	1050.21	4620.96	1929.6	626.31	8227.08
	Cass change	501.21	2024.82	1256.94	468.36	4251.33
	2010					
2014	Shrubland	772.47	607.05	16.11	0.63	1396.26
	Farmland	492.93	2322.36	816.75	234.63	3866.67

Settlement	32.22	1246.5	1127.07	36.63	2442.42
Bareland	0	67.14	319.32	135.27	521.73
Class Total	1297.62	4243.05	2279.25	407.16	8227.08
Class change	525.15	1920.69	1152.18	271.89	3869.91

According to Table 3, there was a cyclic change among the land cover classes. For example, there was a great change of farmland (1855.08 ha) into other classes, while the lowest change was found for bareland (372.51 ha), which changed to other classes from 1995 to 2000. In line with the changes observed between 1995 and 2000, there was a large trend of change from farmland (2024.82 ha) into other land classes between 2000 and 2010 (Table 3). Table 3 also shows that there was a huge trend of change from farmland (1920.69 ha) into other land classes from 2010 to 2014. In this regard, farmlands reduced from 4243.05 ha to 3866.67 ha, while the shrubland cover has increased from 649.53 ha to 1396.26 ha (Table 2).

Effects of area exclosure on vegetation cover

Vegetation cover from 1984 to 2014 (NDVI)

The trend of land use/cover change in the Koraro area (Figure 2). It is crucial to look at whether the area exclosure has brought improvement in vegetation cover. Figure 3 indicates the NDVI values of the study area in the years 1984, 1995, 2000, 2010, and 2014. The study shows that the mean of NDVI values in 1984 was 0.14, whereas the mean value increased to 0.20 in 1995 (Table 4). However, the mean NDVI values have decreased from 0.20 to 0.16 from 1995 to 2000, but improved after 2010, likely due to the implementation of area exclosure since 2006. Overall, the mean, maximum, and minimum NDVI values show spatial and temporal variability (Table 4) (Figure 3).

Table 4. Statistical data of the NDVI values of the vegetation cover of Koraro

Type	Year				
	1984	1995	2000	2010	2014
Mean	0.14	0.20	0.16	0.20	0.20
Maximum	0.51	0.54	0.46	0.54	0.41
Minimum	-0.23	-0.14	-0.15	-0.13	-0.01

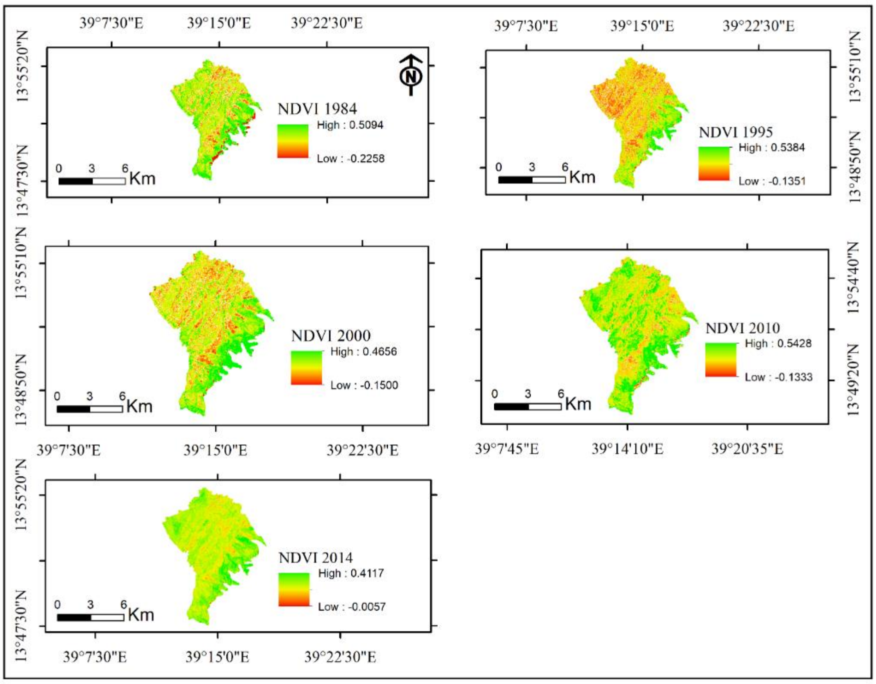

Figure 3. NDVI map of the study area in 1984, 1995, 2000, 2010 and 2014.

Changes in vegetation cover from 1984 to 2014

Figure 4 indicates the detection of the NDVI map among 1984, 1995, 2000, 2010, and 2014. The study demonstrates that vegetation cover has decreased in the northwestern part of the study area, whereas the same cover has increased in the southeastern part between 1984 and 1995. Moreover, the detection changes from 2000 to 2010 and 2014 show there was a rapid increase in the vegetation cover as compared to the previous detection of 1995 to 2000 (Figure 4).

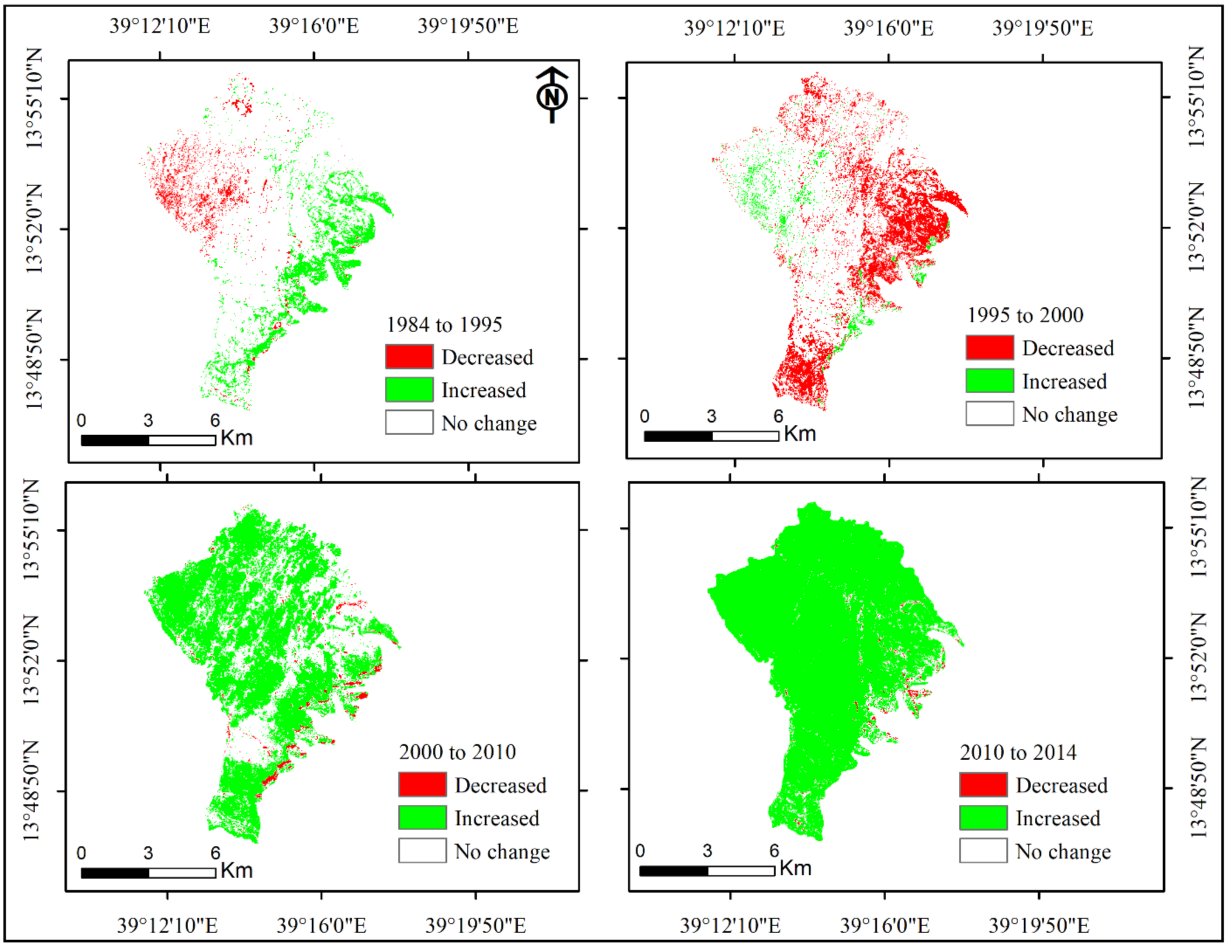

Figure 4. Detection of the NDVI map among the study periods.

Vegetation cover in protected and non-protected areas

The general NDVI map in Figure 3, Table 5, and Figure 5 compares the proportion of vegetation coverage between areas exclosure and without area exclosures. In 2010 and 2014, the NDVI value within the area exclosure was higher than the NDVI values without area exclosures (Table 5 and Figure 5). In line with Hishe et al. (2017), field observations and interviews, the vegetation cover has increased since 2006.

Table 5. The NDVI values of sample points without area exclosure and within area exclosure (WoAE = without area exclosure, WAE= within area exclosure)

Sample points	**2010**			**2014**		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
1 WoAE	0.1	0.19	0.01	0.01	0.19	0.01
2 WoAE	0.14	0.31	-0.03	0.1	0.17	0.048
3 WoAE	0.15	0.3	0.01	0.14	0.21	0.08
4 WoAE	0.15	0.33	-0.02	0.09	0.14	0.04
5 WoAE	0.04	0.17	-0.09	0.1	0.18	0.05
6. WAE	0.2	0.40	0	0.2	0.4	0

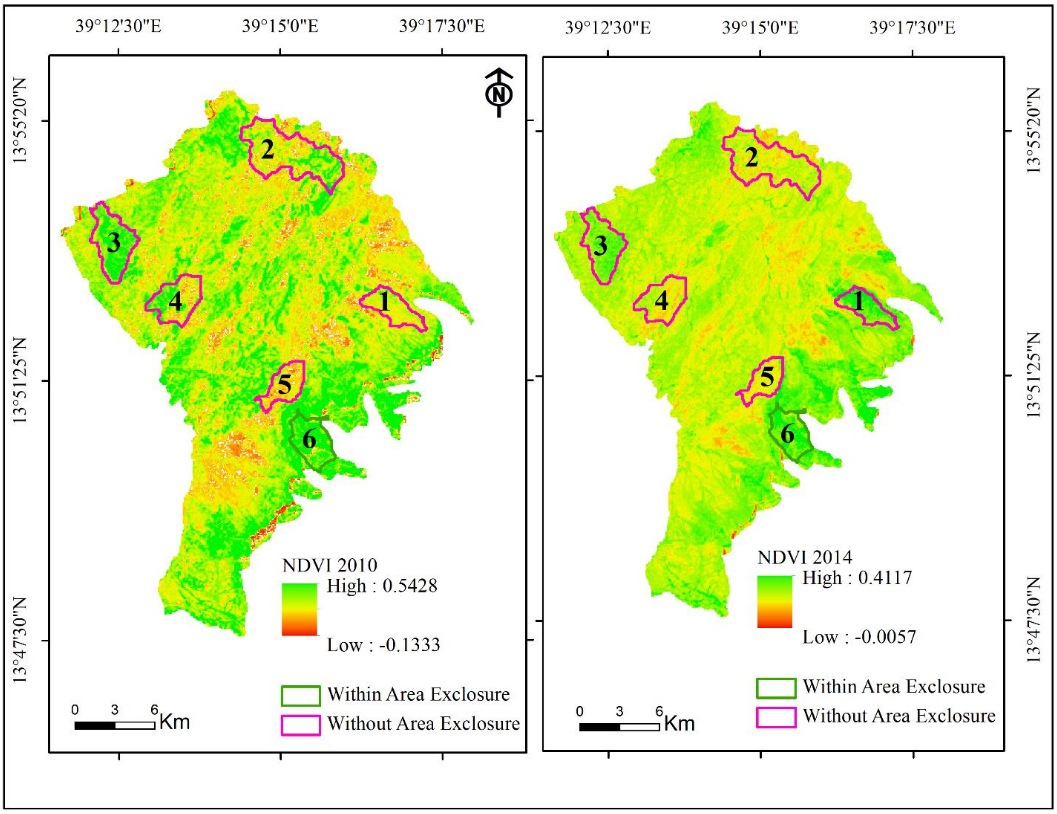

Figure 5. Comparisons of NDVI values within the area exclosure and without the area exclosure.

Effects of area exclosure on the livelihood resources for the local farmers

As demonstrated in Section 3.2, the establishment of area exclosures has significantly enhanced vegetation cover in Koraro village. In terms of local community attitudes towards this practice, the majority of respondents (73%) acknowledged that area exclosure is an effective strategy for restoring previously degraded land into productive ecosystems.

Table 6. The perceived effects of area exclosure on the livelihood of the farmers (Aexp = agricultural experts, HH=household heads)

Effects of area exclosure		Responses					
		Increase		No change		Decrease	
		Frequency	%	Frequency	%	Frequency	%
Reduces of soil erosion	Aexp	4	80	1	20	0	0
	HH	18	72	4	16	3	12
	Total	22	73	5	17	3	10
Increases firewood	Aexp	1	20	0	0	4	80
	HH	2	8	3	12	20	80
	Total	3	10	3	10	24	80
Improves fodder	Aexp	5	100	0	0	0	0
	HH	19	76	3	12	3	12
	Total	24	80	3	10	3	10
Enhanced downstream water	Aexp	5	100	0	0	0	0
	HH	19	76	3	12	3	12
	Total	24	80	3	10	3	10

The establishment of area exclosures along degraded hill slopes has contributed to the improvement of watershed resources for local farmers. In this regard, 80% of respondents reported a decrease in access to firewood from open areas used for livestock roaming, attributed to the expansion of area exclosures (Table 6). Conversely, 10% of respondents indicated that harvesting dead branches and trees within the exclosures provides a source of domestic energy. Additionally, area exclosures have begun to support local firewood supply through recent plantings of fast-growing tree species aimed at ensuring sustainable fuelwood production.

Livestock, often regarded as the "living bank" for farmers, benefits from these exclosures as well. Farmers harvest grass for their livestock within the exclosures, and consistent with observed increases in vegetation cover from 2010 to 2014, access to fodder has improved following the implementation of area exclosures (Table 6). Furthermore, the majority of households (76%) and all agricultural experts surveyed (100%) agreed that fodder availability within the exclosures and their management have increased (Table 6).

Unlike in previous years, key informants reported increased water availability at the foot of the hillsides. Development agents also noted that some farmers have integrated beekeeping activities within the exclosures, generating short-term economic benefits for the community.

Figure 6. Partial view of catchments without area exclosure at the low-lying area (Figure 5, no.2 and no.4).

Based on field evidence, the majority of respondents (72%) residing near area exclosures reported a noticeable reduction in soil erosion within the study area (Table 6). A significant difference in soil erosion rates was observed between untreated and treated watersheds, as illustrated in Figure 6. Similarly, 80% of agricultural experts attributed the reduction in soil erosion to the establishment of area exclosures. Crop productivity has improved on farmlands located at the foot and adjacent to the exclosures, whereas fields bordering open grazing lands continue to experience lower yields, resulting in increased reliance on inorganic fertilizers. On average, farmlands at the foot of hillside area exclosures produced higher yields (32 quintals per hectare) compared to those near open grazing areas (14 quintals per hectare). Detailed production data for common local crops—including wheat, teff, millet, barley, and maize—are presented in Figure 7.

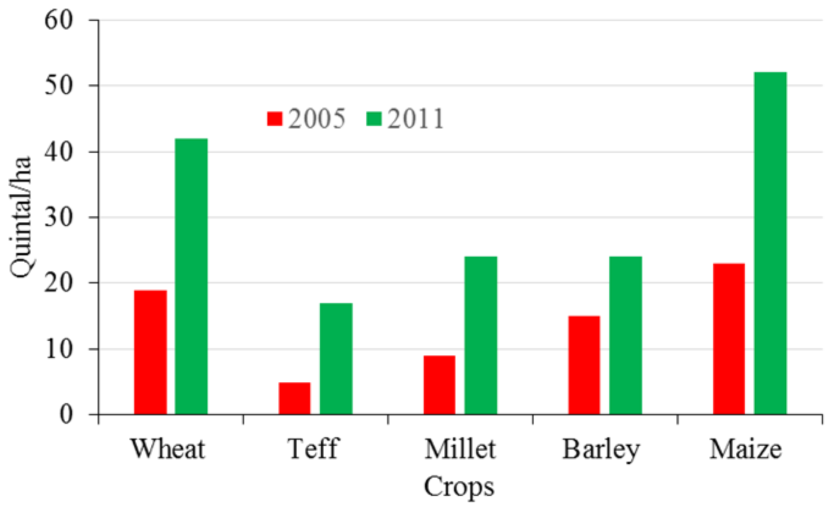

Figure 7. Perceived comparison of yield (quintal/ha) before and after the setup of area exclosure.

Following implementation, some households reported that crop production near the area exclosure has been negatively impacted by rabbits. They also highlighted that limited local participation and unclear rights to utilize exclosure resources undermine the success of this conservation approach. Looking ahead, agricultural experts expressed concern that a shortage of livestock fodder may pose challenges for protecting and managing the emerging grasses within the exclosures. Additionally, local elders reported conflicts between neighboring small villages over grazing rights, stemming from unclear ownership boundaries. The most significant challenge identified for exclosure practices is the growing scarcity of grazing areas. Key informants emphasized that focusing solely on ecological regeneration—expressed in local sayings such as "mine is today and yours is tomorrow" or "take out the livestock"—without addressing current socioeconomic needs, risks rendering area exclosure efforts unsustainable in the study area.

Discussions

The study revealed rapid changes in farmland, bareland, settlement, and shrubland between 1984 and 2014. Specifically, the areas of bareland and farmland decreased, while settlements and shrubland cover increased notably by 2010. The land use/cover change matrix indicates a significant conversion of farmland (2,053.08 ha) into settlements, shrubland, and bareland during the study period. Conversely, illegally constructed settlements were converted into other land use/cover types. In the Anthropocene era, both natural forces and human activities have driven land cover changes (Yesuph & Dagnew 2019). Population pressure is also a major factor contributing to land use/cover changes in the study area. Indeed, population growth in developing countries is widely recognized as a primary driver of agricultural expansion and settlement growth to meet food and housing demands (Lambin et al., 2003; Seto, 2002).

On average, shrubland area increased due to land rehabilitation efforts within the study area. Vegetation cover improved between 2000 and 2014, largely attributed to reduced human disturbances (Table 4). This finding aligns with Birhane (2017), who reported significant vegetation cover improvements resulting from land rehabilitation measures.

Temporal analysis of satellite imagery showed that the mean NDVI values for area exclosures exhibited visible increases from 2010 to 2014, whereas low vegetation cover values persisted in unprotected areas (Figures 6 and Table 5). Furthermore, vegetation detection indicated a rapid expansion of vegetation cover. NDVI analysis revealed marked differences in vegetation cover between treated and untreated watersheds. Consistent with Mekuria (2013) and Mekuria et al. (2019), vegetation cover in the study area was restored between 2006 and 2014 following the establishment of area exclosures on degraded grazing lands. Within the grabens, NDVI values for abandoned settlements—areas with reduced human intervention—increased over time.

Indeed, NDVI values observed in area exclosures were higher than those in open grazing areas. Similarly, Mekuria et al. (2015) documented substantial improvements in vegetation cover due to the protection of areas from human and livestock disturbance. Descheemaeker et al. (2006) further noted that area exclosures facilitate the recovery of vegetation on previously unprotected steep slopes. Therefore, the establishment of area exclosures is an effective tool for restoring degraded lands (Birhane et al., 2017; Mengistu et al., 2005).

Figure 1. Partial view of vegetation status in area exclosure (Figure 5 no.6).

Vegetation cover within area exclosures was found to be significantly higher compared to areas without exclosures (Figure 6 vs. Figure 8). Local communities also observed that the density of shrubs and trees—dominant species within the exclosures—has increased since implementation. This observation aligns with the findings of Abebe et al. (2006) and Birhane et al. (2006), who reported that area exclosures contribute to the restoration of degraded lands and improve watershed resources.

The majority of local residents expressed positive attitudes toward rehabilitation activities through area exclosures. Our study indicates that farmers perceive area exclosures as beneficial to landscape restoration. Farmers' perceptions were strongly linked to the tangible benefits and costs associated with exclosures (Gebregziabher & Soltani 2019). Historically, the area experienced severe shortages of food, fodder, firewood, and timber. Over time, older exclosures have allowed the harvesting of dead branches and trees for domestic energy use. Consistent with Mekuria et al. (2019), exclosures have increased the aboveground biomass of shrubs and trees, thus supporting firewood supply. Moreover, they have enhanced soil quality, boosted ecosystem carbon stocks, increased dry-season water flow, reduced surface runoff, and improved groundwater recharge—ultimately increasing the economic benefits for local communities (Mekuria et al., 2017).

Properly managed area exclosures have contributed to improved food security and agricultural productivity in the study area. Earlier studies by Babulo et al. (2009) emphasized the economic importance of exclosures in Tigray. Land rehabilitation through exclosures has also been associated with increased woody species diversity and improved soil nutrients in the highlands (Gebremedhin et al., 2018). In addition, exclosure interventions have reduced sheet and rill erosion rates, thereby contributing to soil conservation and increased fodder availability for livestock (Table 6).

According to Yimer et al. (2015), land rehabilitation has significantly enhanced soil moisture and quality, which in turn has supported increased annual crop yields. Protected areas also support better livestock production due to the growth of more diverse and nutritious fodder species (Nyberg et al., 2019). Thus, the restoration of degraded landscapes through exclosures has facilitated livelihood diversification among smallholder farmers.

Despite these positive outcomes, local farmers have reported livelihood challenges associated with exclosures. Many noted that exclosures do not provide short-term benefits, and it may take years before tangible returns are realized. This issue is echoed in studies by Mekuria et al. (2009; 2017), which found that households near protected areas often struggle to access firewood for domestic use. In some cases, smallholder farmers have resorted to illegally harvesting biomass for income generation. Additionally, the shortage of grazing land remains a major constraint affecting the wider adoption and sustainability of exclosure practices.

The long-term success of area exclosures in delivering ecosystem and economic benefits is not guaranteed. Challenges to re-greening degraded lands include limited community involvement, lack of clear management plans, ambiguous institutional responsibilities, and weak benefit-sharing mechanisms (Lemenih & Kassa 2014). Mekuria et al. (2019) also reported that the fuelwood crisis is worsening due to ongoing vegetation degradation, underscoring the urgent need for integrated strategies to address fuelwood shortages in the study area.

While the primary motivation for establishing exclosures is ecological regeneration and biodiversity conservation, it is essential to broaden their purpose toward achieving both environmental and socioeconomic objectives. Exclosures must contribute meaningfully to the livelihoods of communities residing adjacent to protected areas (Gebregziabher & Soltani 2019). With improved access to and fair distribution of resources generated within exclosures, these areas can more effectively restore ecosystem services while also maximizing economic benefits for farmers. Indeed, community support for exclosures is closely tied to the perceived and actual economic gains they receive (Gebregziabher & Soltani 2019). Consistent with Lemenih and Kassa (2014), ensuring fair benefit-sharing and secure land tenure is vital for the long-term success of land rehabilitation through area exclosures.

Conclusion

This study examined the impacts of area exclosure on vegetation cover restoration and the livelihoods of smallholder farmers in Koraro, Eastern Tigray, using multi-temporal Landsat imagery, NDVI analysis, and socioeconomic data. Over the 30-year period from 1984 to 2014, the findings demonstrated significant land cover transformations: a decline in bareland and farmland, and a notable increase in shrubland and settlement areas. The NDVI analysis further confirmed that vegetation cover substantially improved within area exclosures, particularly after the launch of the Millennium Village Project in 2006.

Comparative NDVI values between protected (exclosed) and non-protected areas revealed higher greenness in exclosures, reflecting successful ecological recovery. Beyond biophysical changes, the study also showed that area exclosures positively contributed to local livelihoods. These benefits include improved crop productivity on adjacent farmlands, increased availability of fodder and firewood, reduced soil erosion, and enhanced water availability.

However, challenges remain. The exclusion of livestock, shortage of grazing land, and unclear benefit-sharing mechanisms have led to community dissatisfaction in some cases. These findings underscore the importance of participatory approaches, clear management structures, and integrated livelihood strategies to sustain and scale up area exclosure initiatives.

In conclusion, area exclosures in Eastern Tigray have shown dual benefits: restoring degraded landscapes and enhancing the resilience of local farming systems. To ensure long-term success, such interventions must be supported by complementary measures—such as fair resource access, alternative energy sources, and adaptive management practices—that align ecological restoration with socioeconomic needs.

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Availability of data and materials

The data and materials are available and will be provided on request for readers.

Ethics approval and consent

All authors confirmed that there is no ethical conflict. All authors have read the manuscript carefully and agreed to submit it for publication.

Competing interests

The authors declare that they have no competing interests.

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