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Research article

Land use and land cover changes, and woody vegetation status of the Tsimur Gebriel Monastery in Northern Ethiopia

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A R T I C L E I N F O

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A B S T R A C T

Ethiopian Orthodox churches are significant habitats for endemic and threatened plant species, yet their vegetation status and the land use systems impacting them, are little known. Therefore, this study assessed the land use and land cover changes (LULCC) within a 3 km buffer area and the woody vegetation status of the Tsimur Gebriel Monastery in the Tigray region, Northern Ethiopia. The United States Geological Survey's multi-dated (1986, 1999, and 2018) Landsat imagery was used for LULCC analysis. A supervised classification technique was employed for image classification using a maximum likelihood algorithm. Systematic sampling techniques were used to collect vegetation data (tree species, height, and DBH), using 20 sample plots (20 × 20 m) distanced 100 m apart. The results highlighted that among the five identified LULCC types in the buffer zone of the monastery, the farmland area has expanded from 56 to 78 % at the expense of shrublands between 1986 and 2018. At the monastery, 19 woody tree species from 13 families were identified, with an evenness of 0.5 and a Shannon diversity index of 2.4. The stem density was 336 stems per hectare, and the forest cover was approximately 65 %. *Olea europaea* was the dominant tree species, while *Juniperus procera* showed a lack of regeneration at the monastery. Despite the fair natural regeneration, the monastery exhibited lower species diversity, richness, and evenness. However, the monastery remains an important habitat for rare and threatened tree species and may supply seeds for the restoration of degraded lands. Therefore, establishing exclosures in the buffer zone, strengthening stone walls and enrichment planting of degraded tree species should be implemented to ensure the sustainable conservation of valuable tree species.

1. Introduction

The majority of Ethiopians live in the central and northern highlands, where subsistence farming supports nearly 85 % of the population. The limited agricultural resources in these areas caused the ever-increasing population to overexploit forests, resulting in the remaining forests being dominated by isolated and fragmented patches [1–3]. In the early 1900s, the forest cover in Ethiopia was

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estimated at about 40 % [4]. However, this was reduced to only 2.5 % in the early 1990s. Of this, around 8 % was natural high forest, 18 % woodland, 73 % bushlands, and 0.7 % plantation forest. These reductions were associated with agricultural expansion, overgrazing, overexploitation, industrialization, and urbanization [4–7]. According to the FAO[1] report, the country's forest cover has gradually reversed to about 16 %, since the Ethiopian government introduced and implemented several land restoration strategies in the 2000s, including mass planting, soil and water conservation structures, and the establishment of area exclosures [8].

There are eight distinct vegetation types in Ethiopia, which are distributed from the extreme lowlands of the "Danakil depression" in the northeast (~125 m b s.l.) to the extreme highlands of the "Semien mountains" (4533 m a.s.l.) in the north [9]. Dry Afromontane forest is one vegetation type found in an altitudinal range between 1800 and 3000 m a.s.l. in the Ethiopian highlands [10]. Most of the Ethiopian Afromontane forests were secondary forests due to historic disturbances and recovery processes [11]. The remaining fragmented Afromontane forest patches in the northern Ethiopian highlands are mainly found in sacred areas with high economic, ecological, cultural, and religious significance, in protected state forests, and in inaccessible areas [12–14]. Sacred forests are globally important hotspots of biodiversity. For example, in India, more than 50 thousand sacred forests exist, where dry evergreen forest habitats are only found on the southeast coast and have substantial economic and ecosystem values [15].

Evergreen scrub vegetation types and dry Afromontane vegetation types predominate in the highlands of northern Ethiopia, including the target of this study, the Tsimur Monastery [9,10,16]. The remnant forest patches within the church grounds serve as sources of genetic material, havens for biodiversity, and providers of ecosystem services such as erosion prevention and water quality management. In addition, they offer recreational and aesthetic benefits and have the potential to act as carbon sinks [7,14,17]. Nevertheless, some church forests have less dense tree populations, and some species have suffered severe isolation and fragmentation, leaving them without seedlings and saplings [7]. The size of Ethiopian church forests ranges from 1.6 to 100 ha [18,19]. About 35,000 churches and monasteries make up the Ethiopian Orthodox Tewahido Church (EOTC), which are primarily concentrated in the northern and central highlands [19,20].

In addition to its spiritual services, EOTC has a history of protecting sacred forests in its compounds because cutting trees from the church compounds is considered a sinful act. For millennia, this regulation has led to the in situ conservation of threatened flora and fauna species. Despite the protection provided to the church forest by religious regulations, their small size, isolation, and lack of buffer zones make them exposed to anthropogenic disturbances (encroachment) [14,21,22]. Moreover, animal herbivory, trampling, and the gathering of fuelwood also increase the risk of encroachment and biodiversity loss in the isolated church forests of Ethiopia [23–25]. In northern Ethiopia, every village has multiple churches, and they all have conserved a diverse range of local and many threatened plant species [7,13,26]. However, their role in biodiversity conservation has so far received little attention. Thus, it is imperative to conduct research on their genetic resources, ecology, ecosystem services, and their role in genetic conservation [27]. For sustainable restoration and conservation works, it is also essential to have economic, ecological, and conservation data on church forests [28]. The Tsimur monastery was one of the chosen locations for forest development activities by the Ethiopian Orthodox Church Development and Inter-Church Aid Commission, and it was imperative to get base line information before intervention was made. Therefore, the study aims: i) to identify land use and land cover types around the 3 km (km) buffer zone of the Tsimur monastery; ii) to determine the woody species diversity of the monastery; and iii) to characterize the vegetation structure and regeneration capacity of woody species in the monastery.

2. Materials and methods

2.1. Study area

The study was conducted at the Tsimur St. Gebriel Monastery, also known as Tsimur Monastery, in the Enderta district of the Tigray region in Northern Ethiopia, located 19 km northwest of the regional capital, Mekelle city. Geographically, the monastery is located at 13°19′31.1″ N and 39°24′59.5″ E (Fig. 1). The study consisted of two types: one focused on the land use and land cover change in the 3 km buffer area surrounding the monastery, and the second study examined vegetation status solely in the monastery compound. The monastery compound is situated on a sandstone parent rock beneath a cliff, facing north. The elevation of the monastery ranges from 2500 to 2630 m a.s.l. The monastery is characterized by a semi-arid climatic condition, with monthly temperatures ranging from 11 to 27 °C and an average annual precipitation of 550 mm. The primary rainy season runs from the middle of May to the end of August, with bimodal precipitation [29]. Evergreen scrubs and dry evergreen Afromontane forests are the two vegetation types found in the monastery [5,11]. The monastery is located in a fire-shadow area surrounded by farmlands and degraded shrublands. During the "Derg"[2] regime, the monastery administration claimed that there were frequent disturbances and inadequate forest management practices in the monastery.

2.2. Remote sensing data collection

A reconnaissance survey was conducted to provide a general overview of the monastery and to identify the current land use and

[1] FAO forest definition, a forest is defined as "land spanning more than 0.5 ha covered by trees (including bamboo) with a minimum width of 20 m or not more than two-thirds of its Length, attaining a height of more than 2 m and a canopy cover of more than 20 % or trees with the potential to reach these thresholds in situ in due course".

[2] Derg was a military junta that ruled Ethiopia between 1974 and 1991.

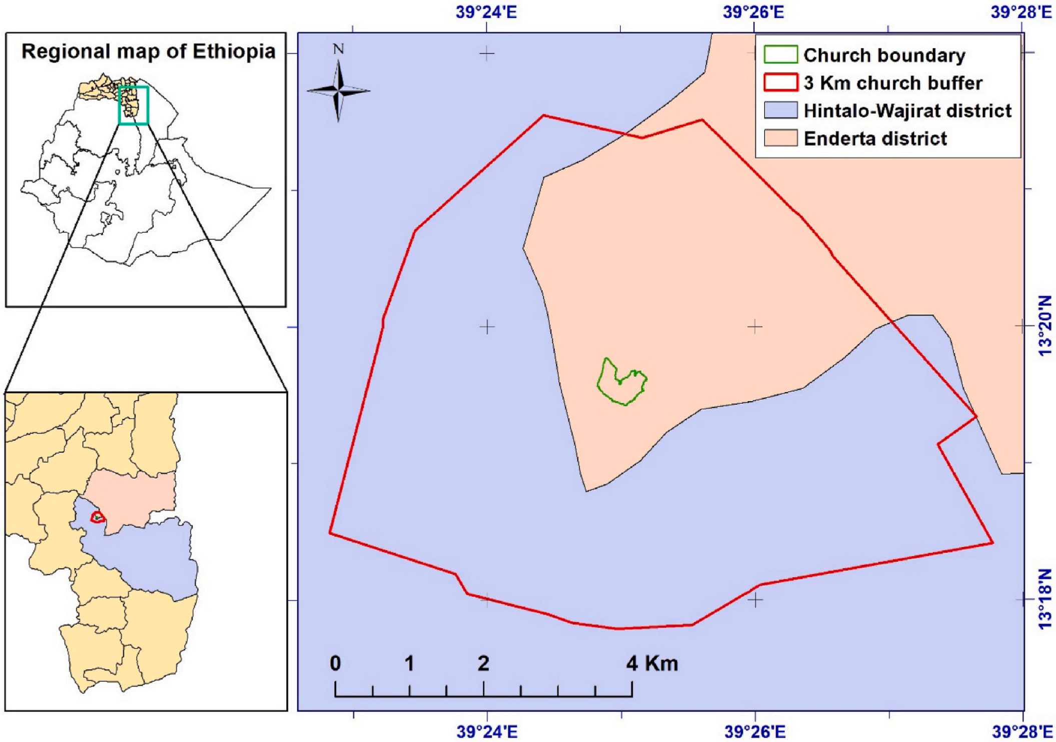

Fig. 1. Geographical location of the Tsimur Gebriel monastery in Tigray region, Northern Ethiopia.

land cover types within the 3 km buffer zone of the Tsimur monastery (Fig. 1). For land use and land cover change (LULCC) analysis, multi-dated Landsat imagery was downloaded from the United States Geological Survey (USGS) archive. Image pre-processing techniques (radiometric and geometric correction) were conducted. The digital numbers of the images were converted to their respective values of Top of Atmosphere. Other pre-processing tasks, such as sub-setting, layer stacking, and image enhancement, were performed to improve the visualization of the images. The spectral bands of the satellite images covering the blue, green, red, near-infrared, and shortwave infrared spectrums (L5 TM: bands 1–5 and 7; L8 OLI: bands 2–7) were selected for analysis (Table 1).

The supervised classification technique was used to classify the images into land use types using a maximum likelihood classification algorithm (Table 2). After pre-processing activities, the Normalized Difference Vegetation Index (NDVI) and other spectral indices were computed to assist in the classification of target classes. In the meantime, GPS sample points (ground truth) for each type of land use were used to calculate the accuracy assessment of each classified image. To assess accuracy, at least 30 random sample points were created for each land use class. A review of the accuracy was conducted on the most recent classified picture. To assess the accuracy of the classified images, kappa statistics and accuracy parameters were computed (Table 3).

2.3. Vegetation data collection

A systematic sampling technique was used to collect vegetation. Since the monastery was the target of the vegetation study, vegetation data was collected only from the monastery compound. To find sample plot points, QGIS software, and the QGIS manual were used to create a 100 × 100 m systematic grid of points. At the grid intersections, approximately 20 plots distanced by 100 m were used for collecting vegetation data (Fig. 2). In the main plot (20 × 20 m size), woody species data were collected for trees with a diameter at breast height (DBH) $\geq$ 5 cm. Subplots (5 × 5 m) were used for recording seedlings and saplings. Trees that had a DBH of <5 cm and a height of at least 0.6 m were classified as seedlings. Trees having a DBH of <5 cm and a height between 0.6 and 1.3 m were classified as saplings [32]. Data on tree species names, DBH, height, crown cover, and altitude were recorded. Tree DBH was measured using a tree caliper, and a diameter tape was used for thicker trees [33,34]. Tree height was estimated using a clinometer, and for shorter trees, a 3-m graduated stick was used. The diameter of the tree crown was determined by cross-projecting crown edges, and the mean crown diameter was then estimated using the formula for the area of a circle. Woody species were identified using the book "Flora of Ethiopia and Eritrea" [35,36].

2.4. Vegetation data analysis

Species diversity: woody species diversity was calculated using the Shannon-Wieners diversity index (H') with the PAST biodiversity software [37]. Additionally, the evenness index was computed to determine the commonness or rarity of tree species in the

Table 1
Attributes of remote sensing images used for this study.

Study years	Image type	Scene (Path/Row)	Pixel size (m)	Acquisition date
1986	Landsat 5 _TM	168/051	30*30	January 05, 1986
1999	Landsat 5_TM	168/051	30*30	January 25, 1999
2018	Landsat 8_ OLI_TIRS	168/051	30*30	February 22, 2018

Table 2
Identified land use types and their descriptions in the study area [30].

Land use types	Descriptions
Bare land	Land covered with vascular plants, composed of exposed rock, sand, and soil surface.
Shrub land	Land with shrubs or bushes with a canopy cover of ≤10 %. Shrubs and bushes are woody perennial plants, 2 m in height at maturity in situ.
Farmland	Part of the land is prepared mainly for growing agricultural crops.
Forest land	Land spanning at least 0.5 ha covered by trees attaining a height of at least 2 m and a canopy cover of at least 20 %
Wetland	Wet areas are often dominated by grasses; most of these areas are waterlogged.

Table 3
Producer and user accuracy of remote sensing data [31].

		Real					Total	User Accuracy (%)
		Bare land	Farmland	Forest	Shrub land	Wetland		
Prediction	Bare land	**19**	10	0	1	0	30	63.3
	Farmland	1	**28**	0	1	0	30	93.3
	Forest	0	1	**27**	2	0	30	90.0
	Shrub land	1	1	0	**28**	0	30	93.3
	Wetland	0	1	1	3	**25**	30	83.3
	Total	21	41	28	35	25	150	
	Producer accuracy (%)	90.5	68.3	96.4	80.0	100.0		
	Accuracy: 85 % Kappa: 0.81							

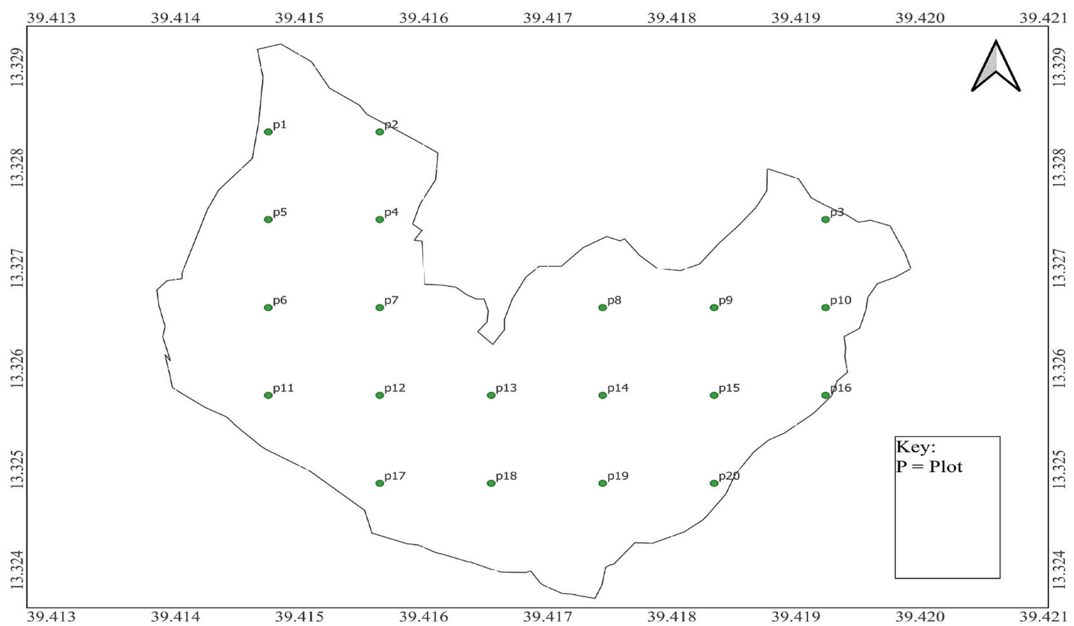

Fig. 2. Location of sampled plots for vegetation survey in the Tsimur monastery compound intersecting at a 100 m × 100 m grid of points.

forest [38,39]. The collected data was analyzed using Microsoft Excel and R software [40]. To characterize the forest, the following vegetation parameters were estimated [41,42].

Basal area (BA): it is the cross section of all trees measured at breast height (1.3 m). In the study, BA was calculated (for trees with DBH ≥5 cm) in m^2 ha^{-1} using the formula for the area of a circle (i.e., $\pi d^2/4$).

Tree density: tree density (stems ha^{-1}) and relative dominance, were estimated for trees with a DBH ≥5 cm, as follows (Eqs. (1)–(4)).

$$Density\ (D) = \frac{\text{number of individuals of a certain species}}{\text{given area}} \tag{1}$$

$$Relative\ density(RD) = \frac{\text{Density of one species}}{\text{Total density}} * 100 \tag{2}$$

$$Dominance(DO) = \frac{\text{Basal area of a species}}{\text{Total area sampled}} \tag{3}$$

$$Relative\ dominanc(RDO) = \frac{\text{Basal area of a given species}}{\text{Basal area of all species}} * 100 \tag{4}$$

Frequency: frequency is defined as the probability of finding a given species in a given area. It is an indicator of how widely distributed a species is across the forest. Tree species frequency was estimated as follows (Eqs. (5) and (6)).

$$Frequency\ (F) = \frac{\text{Number of plots in which a given species occur}}{\text{Total number of plots}} \tag{5}$$

$$Relative\ frequency\ (RF) = \frac{\text{Frequency of a given species}}{\text{Total frequency of all species}} * 100 \tag{6}$$

Importance value index (IVI): IVI is a parameter used to compare the ecological significance of a given species in a forest, and it is estimated as follows (Eq. (7)).

$$IVI = RD + RF + RDO \tag{7}$$

Community structure: the community structure was analyzed by comparing the density of seedlings, saplings, and adult trees throughout the entire monastery [43]. Diameter class distribution was conducted for *Olea europaea*, as it was the most dominant tree species in the monastery. Five diameter classes with a 10 cm interval were created for Olea *europaea* to analyze its stand structure.

Natural regeneration: the regeneration statuses of the woody species in the Tsimur monastery were classified into four classes based on the criteria's in Table 4.

3. Results and discussion

3.1. Classification accuracy

The overall accuracy of the classified image was 85 %, with Kappa statistics of 0.81 (Table 5). The accuracy of the study showed almost perfect agreement between the ground truth and the classified image [45]. The accuracy is in agreement with other studies conducted in comparable areas, for example, in South Gondar, northern Ethiopia [46].

3.2. Land use and land cover changes

Five land use and land cover types were identified in the 3 km buffer zone of the monastery (Fig. 3). Continuous land use and land cover changes were detected during the study period in the study area. In 1986, about 96 % of the land was covered by shrubland and farmland, while forest, bare land, and wetland account only 4 %. Between the three study periods (1989, 1999 and 2018), only shrubland and farmland showed considerable variability. In the period 1986–2018, shrubland decreased from 40 to 18 %, while farmland increased from 56 to 78 % (Table 6).

For the last three decades, the expansion of farmland at the expense of shrublands has been observed in the 3 km buffer zone of the Tsimur monastery. This is in agreement with other reports from studies in northern Ethiopia, for example, in South Gondar, Raya Valley, and Gilgel Tekeze areas in northern Ethiopia [22,47,48]. The Ethiopian highlands are known for their dense population and small farmland size; therefore, it is not surprising to witness the expansion of farmland at the expense of other land use types. Moreover, the poor land use policy and unclear ownership system in the country exacerbate the problem. In addition, many church

Table 4
Classification criteria for regeneration status [44].

Regeneration status	Classification criteria
Good regeneration	If the number of seedlings > saplings > mature trees
Fair regeneration	If the number of seedlings > or ≤ saplings ≤ mature trees
Poor regeneration	If the species survives only in the sapling stage
No regeneration	If a species is present only as a mature tree

Table 5
Image classification accuracy for the Tsimur monastery.

		Real					Total
		Bare land	Farmland	Forest	Shrub land	Wet land	
Prediction	Bare land	19	10	0	1	0	30
	Farmland	1	28	0	1	0	30
	Forest	0	1	27	2	0	30
	Shrub land	1	1	0	28	0	30
	Wetland	0	1	1	3	25	30
	Accuracy: 85 % Kappa: 0.81						

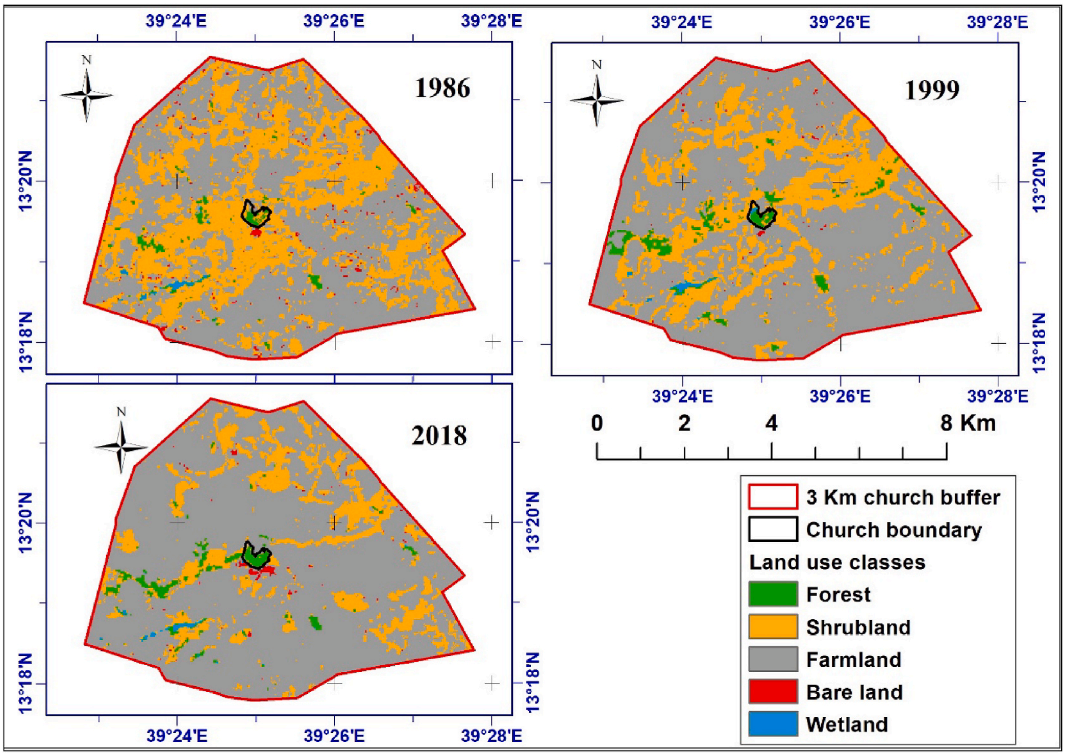

Fig. 3. Land use land cover map of the Tsimur monastery from 1986 to 2018 with a 3 km buffer zone.

Table 6
Land use types and land cover change from 1986 to 2018 in the Tsimur monastery.

Land use types	1986		1999		2018	
	ha	%	ha	%	ha	%
Bare land	87	2	36	0.9	50	1.2
Farm land	2347	56	2881	68.7	3278	78.1
Forest	76	1.8	123	2.9	101	2.4
Shrub land	1670	39.8	1140	27.2	753	18
Wetland	16	0.4	16	0.4	14	0.3
Total	4196	100	4196	100	4196	100

forests are surrounded by agricultural land, shrubland, and settlements [49]. A review of land use and land cover changes around church forests in northern Ethiopia revealed that farmland expansion, settlement, overgrazing, poor policy, and human pressure are the main factors contributing to reducing the natural buffer around churches. These factors have made forest edges vulnerable to grazing and fuelwood collection [21,25,50]. However, despite the dramatic land use changes in the buffer area, church forests showed resilience due to religious rules and stone wall fences around the perimeters of the church compound [25,49]. The forest cover detected (<2 %) between 1986 and 2018 was mainly from the monastery compound. The forest cover showed a slight increase from 1.8 % in 1986 to 2.4 % in 2018. However, the absence of forests outside the monastery compound indicates that the Tsimur monastery has been isolated and fragmented for decades, with limited opportunities for seed dispersal. In the Tigray region, establishing area exclosures in degraded forests has brought a significant restoration of different plant species [51,52] which can be adopted in this study site.

3.3. Floristic composition and diversity

A total of 19 woody species (12 trees and 7 shrubs) from 13 families were identified in the monastery (see Appendix A). Among them, five species were detected only with DBH less than 5 cm as treelets.[3] These species include *Osyris quadripartita, Rhus vulgaris, Maytenus senegalensis, Acacia abyssinica, and Grewia molle*. This could be due to their shrubby nature, and they can occasionally reach a DBH of more than 5 cm. All the woody plant species were indigenous, except for *Eucalyptus camaldulensis* and *Cupressus lustanica*, which are exotic species.

The Tsimur monastery exhibits low diversity, richness, and evenness of woody tree species compared to other church forests in northern Ethiopia (Table 7). However, our result is still within the range of other studies in northern [14,20,32] and central [53] Ethiopia. The low diversity in the Tsimur monastery could be attributed to the small forest size (22 ha), narrow elevation gradient (only 100 m), forest fragmentation (resulting in poor seed dispersal), unsuitable abiotic factors (such as soil quality, north-facing aspect, and low precipitation levels), and severe historical disturbances [13,14,54].

The evenness value (0.56) at our study site indicates a poor representation of individual tree species in the monastery. Compared to other church forests in Ethiopia, our study area shows poor evenness (Table 7). Vegetation distribution is influenced by climate, soil, topography, and disturbance. Due to the hilly topography of the monastery, most species were forced to grow in a confined, suitable habitat at the bottom of the cliff. Therefore, unless expanded by plantations, site suitability could be one reason for the poor evenness [7]. Moreover, anthropogenic disturbance could be another factor contributing to the poor evenness; for example, the monastery administration informed us about the overharvesting of *Juniperus procera* for the construction of the church buildings in the late 1900s. Therefore, the poor diversity and evenness values indicate that there is a lot of work to be done to balance the abundance of tree species and increase the floristic composition and species distribution in the monastery. Otherwise, this forest ecosystem would be less resilient and more vulnerable to disturbances and local species extinction. Infact, it is reported that the dry Afromontane forests in Ethiopia are generally under degradation in species composition, evenness, and tree density, and more efforts are expected to reverse the current situation [11].

3.4. Vegetation structure

BA: The total BA of the forest was approximately 11 m^2 ha^{-1}. This result is lower than those of other nearby monasteries, such as Yemrehane Krstos [60] and Sesa Mariam [61], but higher than those of Gatira Giorgis [59]. *Olea europaea* was the most dominant species (6.4 m^2 ha^{-1}), followed by *Ekebergia capensis* (see Appendix B) at Tsimur Monastery. This was similar to the Yemrehane Krstos monastery in Amhara, which had both *Olea europaea* and *Juniperus procera* as dominant species. However, *Juniperus procera* was less dominant at our study site, possibly due to historic logging for church construction. The BA found in the Tsimur monastery for *Olea europaea* was very low when compared to Tara Gedam, a nearby monastery [50]. Due to the low BA and the dominance of mid-sized trees (with an average height of 7 m), the total volume was also low (3.3 m^3 ha^{-1}). This indicates poor stocking and inadequate silvicultural management at the monastery. Most Ethiopian dry forests also have a history of low productivity and ineffective silvicultural management [11].

Crown cover: The crown cover in the Tsimur monastery was approximately 65 %. This result falls within the range of other studies in northern Ethiopia, e.g., in many churches in the Amhara region [19]. Over half of the crown cover in the Tsimur monastery was contributed by *Olea europaea*. This good crown coverage prevents soil erosion by intercepting raindrops, reducing soil erodibility, and improving nutrient availability through litter fall. Furthermore, since *Olea europaea* seedlings prefer shade for growth, a good crown cover may increase the survival rate of *Olea europaea* seedlings [16,20]. This might have had an impact on the observed healthy regeneration of *Olea europaea* in the monastery (Table 7).

Tree density: The total density of woody plants was 336 stems ha^{-1}, with Olea europaea being the most abundant species (72 %), followed by Jasminium abyssinica (7 %). The total density in the Tsimur monastery is significantly low compared to other studies conducted in the Tara Gedam (3001 stems ha^{-1}), the Abebayehu forest (2850 stems ha^{-1}) [50], and the Yemrehane Krstos church (507 stems ha^{-1}) in the Amhara region of northern Ethiopia [60]. Most of the tree species on our study site were of low density (see appendix B). The low tree density in the Tsimur Monastery could be attributed to poor site suitability, isolation, small forest size (only 22 ha), fragmentation, and historical disturbances. In the Tsimur monastery, there was no forest outside of the monastery compound, which could lead to limited seed dispersal and an edge effect.

Frequency: The most frequent woody species were Olea europaea (100 %) and Juniperus procera (36 %) (see Appendix B). Similarly, these species were the most frequent in the Yemrehane Krstos church [60]. The rest of the species in the Tsimur monastery were mainly confined to water sources and more fertile soils, likely due to habitat preferences. Juniperus procera was found in low density, but its frequency indicates that it grows across a wide range of elevations.

IVI: Olea europaea was found to have a higher IVI value compared to the other species, indicating its high ecological significance and habitat suitability. Compared to trees with a high IVI value, trees with a low IVI value require more conservation efforts [62]. High

[3] Treelets are single-stemmed woody plants less than 5 cm DBH and more than 2 m tall.

Table 7
Comparison of the Tsimur monastery with other sites in northern Ethiopia on woody species diversity, richness, and evenness.

Site	Author/sources	Elevation range (m)	Shannon (H′)	Richness	Evenness
Tsimur monastery	*Present study*	2530–2630	2.34	19	0.56
Yerere mountain	[55]	2400–2700	2.14	18	0.74
Saleda yohannes church	[56]	500–3955	3.8	50	0.84
Tara Gedam monastery	[50]	2142–2484	2.98	111	0.65
Zengena forest	[57]	–	2.74	50	0.7
Debrelibanos church	[58]	–	3.1	59	0.77
Gatira Georgis church	[59]	–	2.78	34	0.88

IVI values were documented for *Olea europaea* species in the Zijje Maryam [63] and in the Gatira Giorgis church in the Amhara region of northern Ethiopia [59]. On the other hand, trees with low IVI values, such as *Juniperus procera* and *Nuxia congesta Fersen* (see Appendix B), should be given priority for enrichment planting and in situ conservation.

Community structure: In comparison to the older trees, the community structure shows a higher number of seedlings and saplings (Fig. 4a). An inverted J-shape is shown in the structure, which is essentially a sign of a healthy structure. The quantity of seedlings was, nevertheless, less than expected in a healthy forest ecosystem. Furthermore, the number of adult trees, saplings, and seedlings differs among species. Species such as *Juniperus procera, Osyris quadripartite, and Nuxia congesta Fersen* have extremely poor tree density and population structure, while *Dovyalis abyssinica, Olea europea and Heteromorpha trifoliate* show a healthy stand structure (Fig. S1). The abnormal population structure for most of the species indicates the need for enrichment planting and modifying the microclimate for better performance.

In the Tsimur monastery, the recorded mean diameter was 16 cm, with a minimum and maximum DBH of 5 cm and 55 cm, respectively. The diameter class of *Olea europaea* displayed an inverted J-shape at the Tsimur monastery, indicating a healthy stand structure in the forest (Fig. 4b). The monastery's recorded minimum and maximum heights were 1.4 and 16 m, respectively, with a mean height of 5.7 m. The majority of the trees were small, with an average height of about 7 m.

Natural Regeneration: Tree regeneration varied among species, with 26 % classified as good, 26 % as fair, 26 % as poor, and 21 % with no sign of regeneration (Table 8; Fig. S1). *Olea europaea* exhibited good regeneration status, whereas *Juniperus procera*, *Nuxia congesta fersen*, and *Dovyalis abyssinica* showed no sign of regeneration. The *Olea europaea* and *Juniperus procera* species were found to have good regeneration status in other neighboring monasteries, such as the Saleda Yohannes in northern Ethiopia [56]. The variation in regeneration status with other church forests may be attributed to differences in tree stockings and historical forest management practices. A stone wall was reported to increase the natural regeneration of trees by protecting against animal intrusion into church compounds [49]. *Juniperus procera* is currently at risk of local extinction due to a lack of mother trees in the Tsimur monastery. The monastery administration stated that *Juniperus procera* was intensively used for church construction in the past. Due to termite resistance and durability, *Juniperus procera* has been the ideal construction material for larger buildings and most churches in Ethiopia [64]. Moreover, most of the dry forests in northern Ethiopia had low rates of regeneration and a declining species composition [11]. The study site has a northerly aspect, which was reported to have a negative correlation with the natural regeneration of some tree species due to insufficient sunlight [65].

3.4.1. Limitations of the study

The study focused on the status of woody plants within monastery grounds but could have included climbers, grasses, herbs, and soil seed banks for a comprehensive understanding of the ecosystem. Furthermore, researching the plant and animal species present in the nearby church forests could provide valuable insight into biodiversity conservation efforts in the region.

4. Conclusions

The LULCC study in the 3 km buffer area revealed the absence of buffer forests or shrubland around the monastery; rather, the expansion of farmland was detected at the expense of shrublands. This indicates the presence of an edge effect and the monastery's continued vulnerability to degradation and deforestation. Therefore, these threats could be mitigated by establishing area exclosures and by establishing stone walls surrounding the monastery compound in consultation with stakeholders.

The monastery is an isolated 22-ha forest patch with limited opportunities for seed dispersal. Despite the poor woody species diversity and evenness, the monastery still serves as a sanctuary for a few locally threatened tree species, offering the genetic material needed for further reproduction and forest restoration activities. *Olea europaea* was the most dominant and frequent species with good natural regeneration in the monastery, whereas *Juniperus procera* lacked seedlings, facing local extinction. The poor diversity, evenness, and density in the monastery should be improved through enrichment planting to build a resilient ecosystem. Consequently, we recommend future studies include shrubs, grasses, and climbers to get comprehensive vegetation information and to design a sustainable forest management plan in the monastery.

Data availability statement

Data will be made available on demand, from the corresponding author.

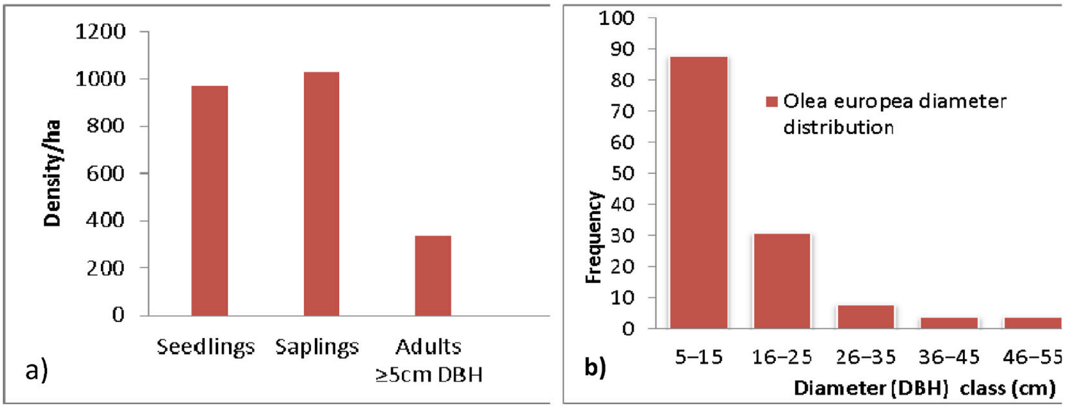

Fig. 4. (**a**) Community structure; (**b**) Diameter class distribution of *Olea europaea* in the Tsimur monastery.

Table 8
Regeneration status of woody plant species in the Tsimur monastery.

Good regeneration	Fair regeneration	Poor regeneration	No regeneration
Olea europaea	Grewia molle	Acacia abyssinica	Juniperus procera
Jasminium abyssinica	Maytenus arbutifolia	Ekebergia capensis	Dovyalis abyssinica
Heteromorpha trifoliata	*Eucalyptus camaldulensis*	Osyris quadripartita	Cupressus lustanica
Aba teumay (Local.name)	Rhus vulgaris	Rhus retinorrhoea	Nuxia congesta Fersen
Euclea shimpri	Olea capensis	Maytenus senegalensis	–

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CRediT authorship contribution statement

Abraha Hatsey: Abraha, Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nesibu Yahya:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Abeje Eshete:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Tesfay Gidey:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Abraha Hatsey reports financial support was provided by Ethiopian Orthodox Church Development and Inter-Church Aid Commission. Abeje Eshete reports a relationship with Ethiopian Orthodox Church Development and Inter-Church Aid Commission that includes: funding grants.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e34200.

List of woody plant species recorded at Tsimur monastery and their families, vernacular names and growth habits.

No.	Scientific name	Family	Vernacular name/Tigrigna	Growth habit
1.	*Acacia abyssinica*	*Fabaceae*	*Chea**	Tree
2.	*Cupressus lustanica*	*Cupressaceae*	*Tsihdi ferenji*	Tree
3.	*Dovyalis abyssinica*	*Flacourtiaceae*	*Mongolhats*	Shrub
4.	*Ekebergia capensis*	*Meliaceae*	*Kot*	Tree
5.	*Eucalyptus camaldulensis*	*Myrtaceae*	*Keyh bahrzaf*	Tree
6.	*Euclea shimpri*	*Ebenaceae*	*kelio*	Shrub
7.	*Grewia molle*	*Malvaceae*	*Hari haroy**	Tree
8.	*Heteromorpha trifoliata*	*Apiaceae*	*Mirkus zebi*	Tree
9.	*Jasminium abyssinica*	*Oleaceae*	*Aba tselim*	Tree
10.	*Juniperus procera*	*Cupressaceae*	*Xihdi habesha*	Tree
11.	*Maytenus arbutifolia*	*Celastraceae*	*At at*	Shrub
12.	*Maytenus senegalensis*	*Celastraceae*	*Kebkeb**	Shrub
13.	*Nuxia congesta Fersen.*	*Stilbaceae*	*Tekuarie*	Tree
14.	*Olea capensis*	*Oleaceae*	*Hamat awlie*	Tree
15.	*Olea europaea sub. cuspidata*	*Oleaceae*	*Awlie*	Tree
16.	*Osyris quadripartita*	*Santalaceae*	*Karets**	Shrub
17.	*Rhus retinorrhoea*	*Anacardiaceae*	*Tetaelo*	Tree/Shrub
18.	*Rhus Vulgaris*	*Anacardiaceae*	*Atami**	Shrub
19.	*Aba tuemay*	*Apiaceae*	*Aba tuemay*	Tree

NB. Vernacular names with * are species detected only at the regeneration study (trees with DBH<5 cm).

Appendix B

Tsimur Monastery woody species (DBH ≥5 cm) density, basal area, abundance, frequency, and IVI values.

No.	Scientific name	Local Name	D	RD	BA	RDO	F	RF	IVI	Rank
1.	*Olea europaea sub. cuspidata*	*Awlie*	241	72	6.4	60.89	100	35	168	**1**
2.	*Ekebergia capensis*	*Kot*	14	4	1.6	15.22	21.4	7.5	27	**2**
3.	*Juniperus procera*	*Xihdi habesha*	9	3	0.55	5.23	35.7	12.5	21	**3**
4.	*Jasminium abyssinica*	*Aba tselim*	25	7	0.47	4.47	21.4	7.5	19	**4**
5.	*Maytenus arbutifolia*	*Ats ats*	9	3	0.12	1.14	21.4	7.5	12	**5**
6.	*Nuxia congesta Fersen.*	*Tekurie*	2	1	0.73	6.95	7.1	2.5	10	6
7.	*Bersama abyssinica Fersen.*	*Mirkus zebi*	7	2	0.36	3.43	14.3	5	10	7
8.	*Dovyalis abyssinica(A.Rich)*	*Mongolhats*	9	3	0.09	0.86	14.3	5	8.9	8
9.	*Rhus retinorrhoea*	*Tetaelo*	7	2	0.07	0.67	14.3	5	7.7	9
10.	*Eucalyptus camaldulensis*	*Keyh bahrzaf*	5	2	0.01	0.1	7.1	2.5	4.6	10
11.	*Olea capensis*	*Hamat awlie*	2	1	0.06	0.57	7.1	2.5	4.1	11
12.	*Aba tuemay*	*Aba tuemay*	2	1	0.03	0.29	7.1	2.5	3.8	12
13.	*Euclea shimpri*	*kelio*	2	1	0.01	0.1	7.1	2.5	3.6	13
14.	*Cupressus lustanica*	*Tsihdi ferenji*	2	1	0.001	0.01	7.1	2.5	3.5	14
	Total		**336**	**100**	**10.51**	**100**	**100**	**100**		

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