

Research

Ecological study and forest degradation of the Waldiba Monastery woodland in Tigray, Ethiopia

Daniel H. Berhe¹ · Abeba N. Retta^{1,2} · Amare S. Tefera¹ · Tesfay Gidey³ · Aklilu Negussie⁴ · Emiru Birhane^{2,5} · Kiros M. Hadgu⁶ · Kflay Gebrehiwot^{7,8}

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Abstract

Sacred sites like monasteries harbour a higher diversity of flora and fauna than nearby unprotected areas and sometimes even higher than protected areas. However, anthropogenic disturbance puts woodlands in these monasteries and churches under significant threat. To study the floristic composition and forest degradation of Waldiba monastery woodland in Tigray, Ethiopia, 30 plots were established along transect lines. We recorded 39 native woody species (33 trees, 5 shrubs and 1 liana) belonging to 19 families. The woodland had a Shannon diversity index of 3.10, Simpson similarity index of 0.94, evenness of 0.58 and dominance of 0.06. The density of woody species was 922 stems ha⁻¹ with a total basal area of 49.27 m² ha⁻¹. The tree species with higher importance value index (IVI) value were *Dichrostachys cinerea* (86.04%), *Combretum fragrans* (71.87%), *Combretum hartmannianum* (60.30%) and *Combretum* sp. (50.15%). The population structure of the woody species exhibited various patterns; bell shape, irregular shape, interrupted J shape, and J shape. Plant regeneration was inadequate for most of the tree species. *Vachellia venosa* is listed as endangered while *C. hartmannianum* as vulnerable in the IUCN red list species category. Waldiba dry woodland has undergone significant cover changes. Waldiba has lost much (65%) of its dense forest and open forest (44%) mainly due to anthropogenic disturbance. The woodland with its biodiversity is under threat. In effect, the species with low IVI, species listed in the IUCN red list and those species with none to poor regeneration status should be prioritized for in situ and ex situ conservation intervention to avert the threat. Research on reproductive ecology of the threatened indigenous species is imperative, as the woodland should be managed for ecosystem services and biodiversity conservation.

Keywords Analytical hierarchy process (AHP) · Anthropogenic disturbance · Dry woodlands · Monasteries · Floristic composition · Importance value index (IVI) · Regeneration

✉ Daniel H. Berhe, danielhgs829@gmail.com; Abeba N. Retta, abebanigussie1984@gmail.com; Amare S. Tefera, c.amaresisay@gmail.com; Tesfay Gidey, tglove.gidey@gmail.com; Aklilu Negussie, aklilumekuria@weforest.org; Emiru Birhane, emiru.birhane@mu.edu.et; Kiros M. Hadgu, kirhadgu@gmail.com; Kflay Gebrehiwot, kflay77@gmail.com | ¹Department of Natural Resources Management, University of Adigrat, P.O. Box 50, Adigrat, Ethiopia. ²Department of Land Resources Management and Environmental Protection, College of Dryland Agriculture and Natural Resources, Mekelle University, P.O. Box, 231, Mekelle, Ethiopia. ³Department of Plant Science, College of Agriculture and Environmental Sciences, University of Adigrat, P.O. Box 50, Adigrat, Ethiopia. ⁴WeForest, Addis Ababa, Ethiopia. ⁵Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences (NMBU), Postboks 5003, 1432 Ina, Ås, Norway. ⁶World Agroforestry (ICRAF) - Ethiopia, c/o ILRI Ethiopia, P. O. Box 5689, Addis Ababa, Ethiopia. ⁷Department of Biology, Samara University, P. O. Box 132, Semera, Ethiopia. ⁸Applied Behavioural Ecology and Ecosystem Research Unit, School of Ecological and Human Sustainability, University of South Africa, Private Bag X5, Florida 1710, South Africa.



1 Introduction

Tropical dry forests are forests in dryland areas that are distinguished by their marked dry season and low water availability. They have a ratio of potential evapotranspiration to precipitation between one and four and typically experience three to eight months of drought [1]. Dry tropical forests cover more than 40% of the global tropical forest area [2–4]. The largest proportion of dry forest is found in Africa [1, 3], which has an area of 17.3 million km² [5]. Dry forests and woodlands are the largest remaining forest resources and cover 55 million ha in Ethiopia [4, 6, 7].

Dry tropical forests contain a wealth of unique biodiversity of immense local, regional and international significance [2, 8]; are home to half a billion people [2, 4]; directly support the livelihood of one billion people worldwide [1] and approximately 52 million rural households in the Horn of Africa [9]. For instance, tapping and grading of frankincense and natural gums in the drylands create seasonal employment opportunities for 20,000 to 30,000 people in Ethiopia [10]. The unique feature of dry forests and woodlands of Ethiopia is their richness with major gum and resin bearing species of *Acacia*, *Boswellia* and *Commiphora* [2, 4] that have high cultural, religious, economic and ecological significance [2, 7]. Despite this fact, dry forests remain among the world's most threatened and least protected forests [4, 7, 8]. Until recently, very little attention has been given to developing, protecting and sustainably managing these valuable resources. However, Ethiopian dry forests are caught in a spiral of deforestation due to competing land uses [2]. For example, in Tigray, one of the largest frankincense-producing areas in Ethiopia, about 170,000 ha of dry forest has been deforested and converted to croplands since the 1970s [3, 4].

In Tigray, forest disturbance has a 3000-year history [11, 12]. As a result, large forests have been converted into arable land that the last remaining refugia for native woody plant species are found around churches and monasteries [13–15]. As such, church/monastery forests and woodlands are considered biodiversity hotspots, the last natural seed banks for native tree species, reference areas for local endemism and buffers against depletion and last corner stones for species distribution [13].

Waldiba monastery woodland is one of the natural vegetation types found in Tigray. Founded around 490 AD, the Waldiba monastery is one of the oldest monasteries found in Africa. The monastery is situated in a remote area surrounded by mountains, rivers, deep gorges, and valleys. As a sacred place of worship, its resources are, traditionally, considered to be under God's protection and thus off limits for resource extraction [38]. Thus, it has conserved patches of many indigenous trees and shrubs in situ [39]. However, like other tropical dry forests, land degradation is rife due to overgrazing, illegal logging and overexploitation of the woodlands, farming of its fragile lands, gold mining, settlement, burning (wildfire) and all of which resulted in clearing of Waldiba monastery woodland [16]. Problems associated with woodland degradation in Tigray have been reported in many studies [3, 17–21]. However, most of these studies emphasis were on the population structure and focused on only single woody species, such as *Boswellia papyrifera* [3, 18, 21, 22], *Adansonia digitata* [17] and *Oxytenanthera abyssinica* [19]. To the best of our knowledge, studies on the floristic composition and forest degradation of the Waldiba Monastery's dry woodland using the Analytical Hierarchy Process (AHP) are scanty. AHP is a method of measurement through pairwise comparisons [23]. It is one of the most widely used multiple criteria decision-making tools in the areas of conservation evaluation and environmental management [18, 24–26] to address land-use problems [27]. It assists decision makers to construct their preferences via criteria weighting and scoring [28].

Understanding floristic composition and forest health is important for biodiversity conservation and management. However, majority of the floristic composition studies [29–34] in Ethiopia were done in the mountain chain highlands. Only a few studies [18, 35–37] have been conducted in the lowland dry woodland areas. Therefore, this study was conducted to (1) assess the diversity of woody species in the woodland (2) determine the population structure and woody species regeneration and (3) identify the drivers of deforestation and forest degradation using a multi-criteria decision model—the AHP in the sacred Waldiba monastery dry woodland.

2 Materials and methods

2.1 Study area

The sacred Waldiba Monastery woodland¹ is situated within the Tselemti district in the north-western zone of Tigray, Ethiopia (Fig. 1). Geographically, it lies between 13° 30' to 14° 00' North and 37° 45' to 38° 15' East in the western lowland

¹ Woodlands are open stands of trees of at least 8 m tall with a canopy cover of 40 percent or more, but never with interlocking crowns and usually with a field layer of heliophilous ('sun-loving') grasses. Woodlands have similar height as forests, but woodlands never have densely interlocking crowns (although the crowns can be in contact) [38]

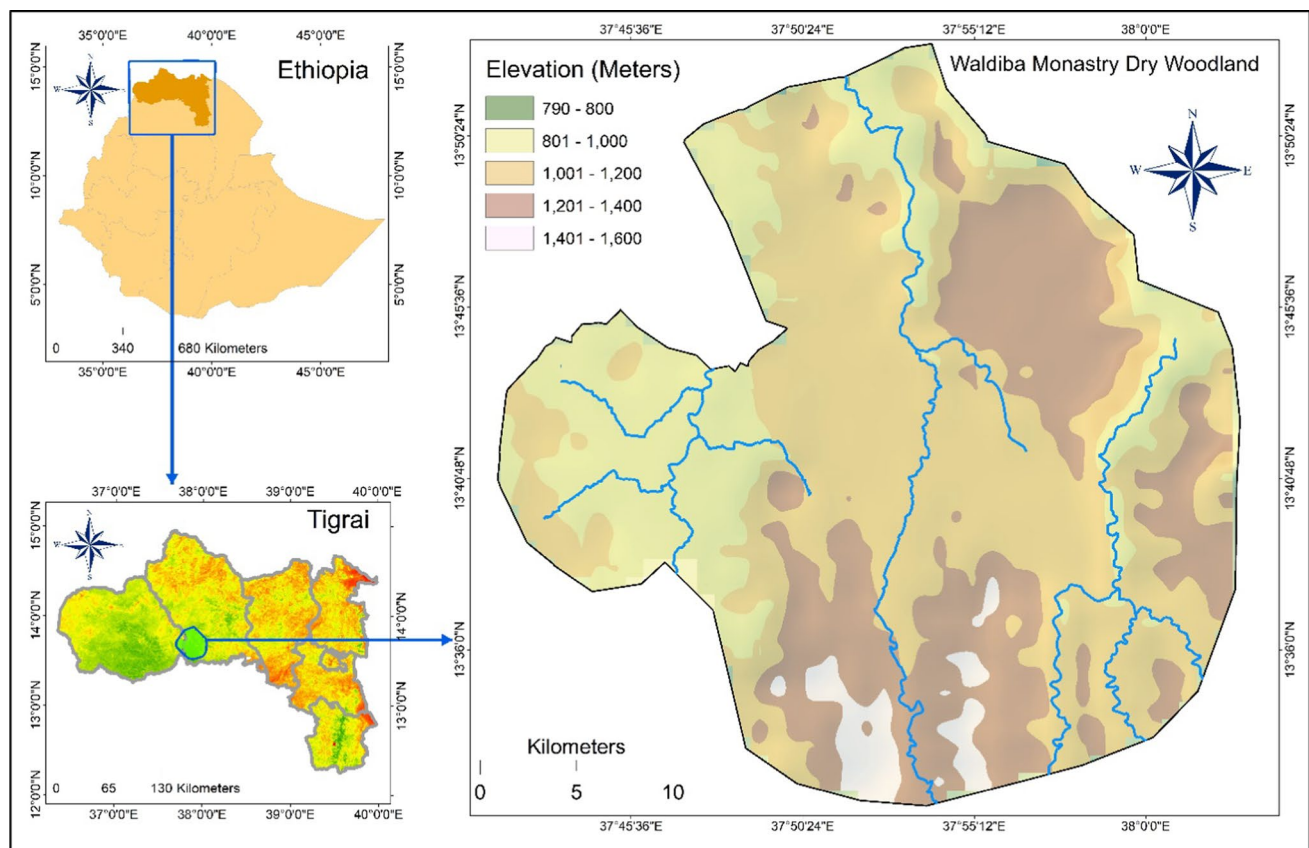


Fig. 1 Location map of Waldiba Monastery dry woodland in Tigray, Ethiopia

(elevation below 1250 m) of Tigray. It is about 450 km from Mekelle, the capital of Tigray. It is bounded by three regional districts (Asgede Tsimbla to the North, Welqait to the West and Tsegede to the South) and by the National Regional State of Amhara to the South. Waldiba monastery woodland forest is the largest state forest with an area of almost 950 km² next to Desa'a forest (1541 km²). The woodland is bordered by the Tekeze, Zarema, Tsotit and Insiya rivers. The monastery forest is surrounded by villages with 47,000 inhabitants. Waldiba receives more than 1000 mm of rainfall annually. Besides, the mean annual temperature is around 26 °C and varies from 40.8 to 49.4 °C for the maximum and from 12.3 to 21 °C for the minimum temperature. The hottest months are March to June. The woodland is a kind of broad-leaved deciduous *Combretum-Terminalia* woodland in physiognomy with varying proportions of woody vegetation and perennial grasses [38].

2.2 Vegetation survey

2.2.1 Vegetation sampling

A systematic sampling² method was employed for the inventory of woody species [36]. In the woodland, we laid parallel line transects in the south-north direction. Along the line transects, sample plots measuring 20 m × 20 m were established at approximately 1 km intervals to measure the trees and shrubs' attributes [39]. Overall, 30 representative sample plots were established in the woodland. Inside the plots, nested subplots of 3 m × 3 m were established to measure sapling/seedling attributes and herb cover.

² Systematic sampling is a type of probability sampling method in which sample members from a larger population are selected according to a random starting point but with a fixed, periodic interval [72].

2.2.2 Vegetation data collection

In each sample plot, vegetation related components such as species composition, density (seedling, sapling, shrub and tree), frequency, diameter at breast height (DBH) for trees, diameter at stump height (DSH) for shrubs and some—saplings and tree height were recorded. Furthermore, environmental and disturbance variables such as topography, illegal logging, livestock pressure and fire incidence were recorded for each sample plot. Diameter tape and Suunto hypsometer were used to measure DBH and height, respectively. All woody species were identified by their local and/or scientific names. Species identification was performed directly in the field using relevant reference materials [40, 41] as well as with the help of local people familiar with the flora [42, 43]. Furthermore, woody species that occurred outside the plots were also recorded to produce a more complete list of the woody plants in the study area. Finally, the woody species were classified into different growth forms based on their height and diameter: Height > 1.5 m and DBH ≥ 2.5 cm were considered trees, a height ≥ 0.50 m and < 1.5 m or DBH/DSH < 2.5 cm as saplings/shrubs and a height < 0.50 m was considered a seedling [44].

2.2.3 Vegetation data analysis

Diversity was analysed using the Shannon diversity index (H) and evenness or equitability index (E) [33, 45]. The Shannon diversity index takes into account species richness and evenness [46] and it usually lies between 1.5 and 3.5 and rarely exceeds 4.5 [47]. A score ≥ 3 is considered high, medium (2–3), low (1–2) and very low when it is ≤ 1.0 [29]. The community types were identified with the multivariate hierarchical clustering (dendrogram) method using Ward's algorithm and based on the Bray–Curtis similarity index [48]. Diversity analysis and hierarchical clustering were performed with PAST software version 3.06 [49]. Likewise, vegetation structure was computed based on density, frequency, DBH and basal area and the importance value index (IVI) using Microsoft Excel [33, 39, 42, 43, 45, 46]. To describe population structure, individuals of the recorded tree species were grouped into 10 diameter classes. The resulting frequency histograms were subsequently interpreted as proxies for regeneration status via frequency histograms. Only tree species with high IVI and one economical flagship tree were considered for analyses of population structure. The IVI and basal area of each tree/shrub species were calculated using the following equations:

$$R_D = \frac{N_i}{\sum_{i=1}^s N_i} \quad (1)$$

where R_D is the relative density of a species and N_i is the number of individuals of the i^{th} species,

$$R_F = \frac{F_i}{\sum_{i=1}^s F_i} \quad (2)$$

where R_F is relative frequency of a species and F_i is the number of occurrences of the i^{th} species;

$$R_{DO} = \frac{B_i}{\sum_{i=1}^s B_i} \quad (3)$$

where R_{DO} is relative dominance of a species and B_i is the total basal area of the i^{th} species

$$B_A = \frac{\pi d^2}{4} \quad (4)$$

where, B_A is basal area, d is the diameter of the tree or shrub

$$IVI = R_D + R_F + R_{DO} \quad (5)$$

2.3 Focus group discussion and key informant interviews

To substantiate the analysis of floristic composition and to identify the major driving forces of deforestation and forest degradation and other relevant nonvisual information, focus group discussion (FGD) and key informant interviews (KIs) were undertaken.

The KI participant were selected using the snow-ball³ method, while the individuals for FGD were selected with the help of a facilitator. A total of 12 individuals representing various stakeholders (NGOs, forest experts, forest guards, monks, herders and gold miners) were selected for the FGD. Then, they were informed about the purpose of the study and were invited to a two-day workshop in Maitsebri town, Tselemti district. In the workshop, the FGD group members were encouraged to talk freely to identify the drivers of deforestation and select the criteria and alternatives for the AHP. To do so, an unstructured questionnaire (a check list) was developed for both the KI interview and the FGD.

The data obtained from FGDs were used to weight and rank the major drivers of cover change using AHP technique as per the procedures outlined in Gidey et al. [25], Gidey et al. [18], and Marques [50]. AHP is one of the best known and most widely used multi-criteria decision making (MCDM) approaches [18, 23, 25, 50]. It allows users to assess the relative weight of multiple criteria or multiple options against given criteria in an intuitive manner. In case quantitative ratings are not available, nature conservationists can still recognize whether one criterion is more important than another [23].

The overall objective of AHP was to identify and select the driving force for forest degradation using the criteria proximate and underlying causes and their respective alternatives. In light of this, we used the proximate and underlying causes of forest degradation as criteria. The alternative proximate causes included: Overgrazing, cultivation (irrigation development, dam construction and settlement), mining, illegal logging and over exploitation (fuelwood, charcoal making, and house construction, poaching, over tapping,⁴ wildfire), biotic factors (insect attack) and abiotic factors (drought-induced tree dieback). The alternative underlying causes included population pressure, poverty, policy (institutional) issues and lack of awareness.

In addition, the floristic composition and AHP results of the woodland were further substantiated by the analysis of land use and land cover (LULC) change for the years 1972, 1986 and 2018.

3 Results

3.1 Vegetation survey

3.1.1 Floristic composition

In our study, we recorded a total of 39 (33 trees, 5 shrubs and 1 liana) indigenous woody species (Table 1) belonging to 19 families. The Combretaceae and the Fabaceae were the dominant families, contributing seven species and six species to the total woody species composition, respectively. The remaining, 17 families, were represented by either two or a single species. This finding does not include the gigantic tree *Adansonia digitata* (Bombacaceae) that was present in the woodland but was not recorded in the sample plots. In the IUCN red list, *C. hartmannianum* is considered as vulnerable while *V. venosa* is considered endangered (<https://www.iucnredlist.org/>).

3.1.2 Plant community types

Three plant community types were identified (Fig. 2); *Combretum–Terminalia*, *Boswellia–Ziziphus* and *Vachellia–Ximenia*. The *Combretum–Terminalia* community occurred at flat plains to hilly slopes between 958 and 1201 m above sea level. The main species in this community were *C. fragrans*, *C. hartmannianum*, *Combretum* sp., *C. molle*, *Terminalia* sp. *T. brownie*, *G. ferruginea* and *G. flavescens*. The *Boswellia–Ziziphus* community type occurred at altitude of 835–1201 m in hilly slopes with shallow soils. The dominant species include *B. papyrifera*, *Z. abyssinica*, *Z. spina—christi*, *Pterocarpus lucens*, *Stereospermum kunthianum*, *Otostegia fruticosa* and *Lannea fruticosa*. The *Vachellia–Ximenia* community type occurred at the altitudinal range of 999–1174 at gentle slopes and in the flat plain with deep soil and also around riverbanks. The main species of this community type include *V. polyacantha*, *V. sieberiana*, *V. etbaica*, *Ximenia americana*, *Tamarindus indica*, *Sterculata setegra*, *Dovyalis abyssinica* and *Diospyros mespiliformis*.

³ Snowball is a method of selecting key informants based on individuals (happen to meet by chance) suggestions.

⁴ Over tapping refers to frankincense production without resting time [18]

Table 1 Tree density ha⁻¹, basal area (BA), relative frequency (RF), relative abundance (RA), relative dominance (RD) and importance value index (IVI) of woody species

Species	Density (Stems ha ⁻¹)	BA (m ² /ha)	RD (%)	RF (%)	RA (%)	IVI (%)
<i>Albizia amara</i> (Roxb.) Boivin	2 (0.00)	0.90 (0.03)	0.22	3.33	1.82	5.37
<i>Anogeissus leiocarpus</i> (DC.) Guill. & Perr.	15 (0.56)	1.87 (0.01)	1.95	23.33	3.79	29.08
<i>Boswellia papyrifera</i> (Caill. ex Delile) Hochst.	29 (0.12)	6.93 (0.00)	3.80	13.33	14.06	31.19
<i>Cissus petiolata</i> Hook.f.	2 (0.09)	0.23 (0.00)	0.22	3.33	0.47	4.03
<i>Cissus petiolata</i> Hook.f.	2 (0.08)	0.00 (0.00)	0.22	3.33	0.01	3.56
<i>Combretum fragrans</i> FHoffm.	48 (0.33)	4.39 (0.08)	6.29	56.67	8.91	71.87
<i>Combretum hartmannianum</i> Schweinf.,	103 (0.52)	3.38 (0.07)	13.45	40.00	6.86	60.30
<i>Combretum molle</i> R.Br. ex G.Don	26 (0.37)	1.63 (0.05)	3.36	26.67	3.31	33.34
<i>Combretum</i> sp.	28 (0.35)	4.83 (0.10)	3.69	36.67	9.79	50.15
<i>Commiphora africana</i> (A.Rich.) Engl.	8 (1.22)	0.11 (0.01)	0.98	3.33	0.22	4.53
<i>Dalbergia melanoxylon</i> Guill. & Perr.	8 (0.35)	0.44 (0.06)	0.98	6.67	0.89	8.53
<i>Dichrostachys cinerea</i> (L.) Wight & Arn.	99 (1.04)	1.54 (0.01)	12.91	70.00	3.13	86.04
<i>Diospyros mespiliformis</i> Hochst. ex A.DC.	3 (1.62)	0.31 (0.04)	0.33	3.33	0.64	4.30
<i>Diospyros mespiliformis</i> Hochst. ex A. DC.	33 (0.35)	0.18 (0.02)	4.34	6.67	0.36	11.36
<i>Dovyalis abyssinica</i> (A.Rich.) Warb.	26 (2.03)	0.37 (0.04)	3.36	10.00	0.75	14.12
<i>Grewia ferruginea</i> Hochst. ex A.Rich.	7 (2.89)	0.28 (0.11)	0.87	6.67	0.56	8.10
<i>Grewia flavescens</i> Juss.	4 (0.00)	0.05 (0.01)	0.54	3.33	0.09	3.97
<i>Jasminum floribundum</i> R.Br. ex Fresen.	7 (2.02)	0.02 (0.01)	0.87	6.67	0.04	7.58
<i>Jasminum grandiflorum</i> subsp. <i>floribundum</i> (R.Br. ex Fresen.) P.S.Green.	25 (1.02)	0.11 (0.00)	3.25	3.33	0.23	6.82
<i>Lannea fruticosa</i> (Hochst. ex A.Rich.) Engl.	19 (0.00)	1.61 (0.05)	2.49	30.00	3.26	35.76
<i>Lonchocarpus bussei</i> Harms (L. <i>laxiflorus</i>)	7 (0.00)	1.40 (0.14)	0.87	16.67	2.85	20.38
<i>Maytenus senegalensis</i> (Lam.) Exell	3 (0.00)	0.26 (0.06)	0.43	6.67	0.52	7.62
<i>Mimusops kummel</i> Bruce ex A.DC.	28 (0.12)	1.37 (0.09)	3.58	13.33	2.78	19.69
<i>Otostegia fruticosa</i> (Forssk.) Schweinf. ex Penzig (<i>O. repanda</i>)	1 (0.00)	0.14 (0.00)	0.11	3.33	0.28	3.72
<i>Oxytenanthera abyssinica</i> (A.Rich.) Munro	15 (0.10)	1.16 (0.05)	1.95	6.67	2.35	10.97
<i>Pterocarpus lucens</i> Lepr. ex Guill. & Perr.	33 (0.16)	1.37 (0.05)	4.23	13.33	2.79	20.35
<i>Sterculia africana</i> Lour.) Fiori	2 (0.00)	1.92 (0.04)	0.22	6.67	3.89	10.77
<i>Stereospermum kunthianum</i> Cham	12 (1.19)	0.72 (0.08)	1.52	16.67	1.47	19.66
<i>Tamarindus indica</i> L.	1 (0.00)	0.35 (0.00)	0.11	3.33	0.72	4.16
<i>Terminalia brownii</i> Fresen	12 (0.00)	3.32 (0.03)	1.52	13.33	6.74	21.60
<i>Terminalia</i> sp.	47 (1.12)	1.99 (0.17)	6.07	16.67	4.05	26.79
<i>Vachellia etbaica</i> Schweinf. Kyal. & Boatwr.	17 (0.01)	0.45 (0.23)	2.17	3.33	0.92	6.42
<i>Vachellia polyacantha</i> subsp. <i>campylacantha</i> (Hochst. ex. A.Rich.) Kyal. & Boatwr	48 (0.06)	2.68 (0.38)	6.29	20.00	5.44	31.73
<i>Vachellia sieberiana</i> (DC.) Kyal. & Boatwr.	4 (0.02)	0.29 (0.00)	0.54	6.67	0.58	7.79
<i>Vachellia venosa</i> Hochst. ex Benth.	3 (0.05)	0.82 (0.00)	0.33	3.33	1.67	5.33
<i>Ximenia americana</i> L.	12 (0.28)	0.35 (0.02)	1.52	16.67	0.72	18.90
<i>Ziziphus abyssinica</i> Hochst. ex A. Rich.	32 (0.69)	1.39 (0.07)	4.12	30.00	2.82	36.94

Table 1 (continued)

Species	Density (Stems ha ⁻¹)	BA (m ² /ha)	RD (%)	RF (%)	RA (%)	IVI (%)
<i>Ziziphus spina-christi</i> (L.) Desf.	3 (0.20)	0.11 (0.00)	0.33	3.33	0.23	3.89
Total	922 (0.96)	49.27 (0.11)	100	100	100	300

Values of density and basal areas are mean (standard deviation)

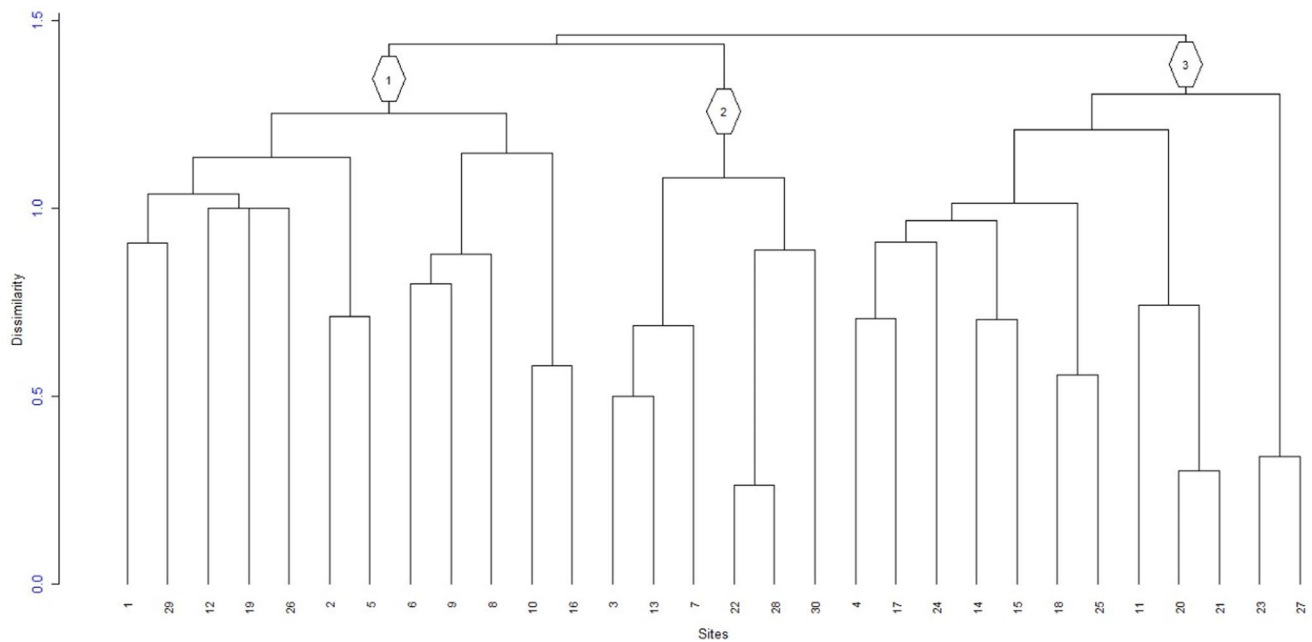


Fig. 2 Dendrogram of the plant communities, *Combretum–Terminalia*, *Boswellia–Ziziphus* and *Vachellia–Ximenia*, found in Waldiba monastery's dry woodland

3.1.3 Woody species diversity

In our study, we found Shannon diversity index, Simpson similarity index, evenness and dominance values of 3.10, 0.94, 0.58 and 0.06, respectively. This indicates that the woodland is relatively high in species diversity, with almost even representation of each species and with low dominance of species.

3.1.4 Frequency, density and dominance

Dichrostachys cinerea was the most frequent species, occurring in 70% of the sampled plots, followed by *C. fragrans* (56.67%), *C. hartmannianum* (40%), *Combretum* sp. (36.67%), and *Z. abyssinica* (30%) (Table 1). This indicates that the woodland is being dominated by thorny species that are less palatable to cattle (Table 1 and Fig. 3). This variation in frequency of species is attributed to their habitat preferences, regeneration ability and disturbance degree.

The five most important woody species in terms of their density were *C. hartmannianum*, *Dichrostachys cinerea*, *C. fragrans*, *V. polyacantha* and *Terminalia* sp. (Table 1), with densities ranging from 47 to 107 stems ha^{-1} . The relative density (RD), which is similar to the density (stems ha^{-1}), also followed the same trend as of the density (Table 1). In terms of dominance (Table 1), the six most dominant tree species contributing to more than 50% of the basal cover were *B. papyrifera*, *Combretum* sp., *C. fragrans*, *C. hartmannianum*, *Terminalia brownii* and *V. polyacantha*. Mostly of these species were found in mature stands with large diameters (up to 50 cm).

3.1.5 Basal area

The total basal area of all the woody species was 49.27 $\text{m}^2 \text{ha}^{-1}$. The woody species with the largest contribution to the basal area can be considered the most important [45, 51]. The species with the largest basal area was *B. papyrifera* [52]. The other five species with the largest basal area contribution were *C. fragrans*, *Combretum* sp., *C. hartmannianum*, *Terminalia brownie* and *V. polyacantha*. Thus, these are considered the most ecologically important species and the difference in basal area could be due to the presence of old growth and large diameter trees.

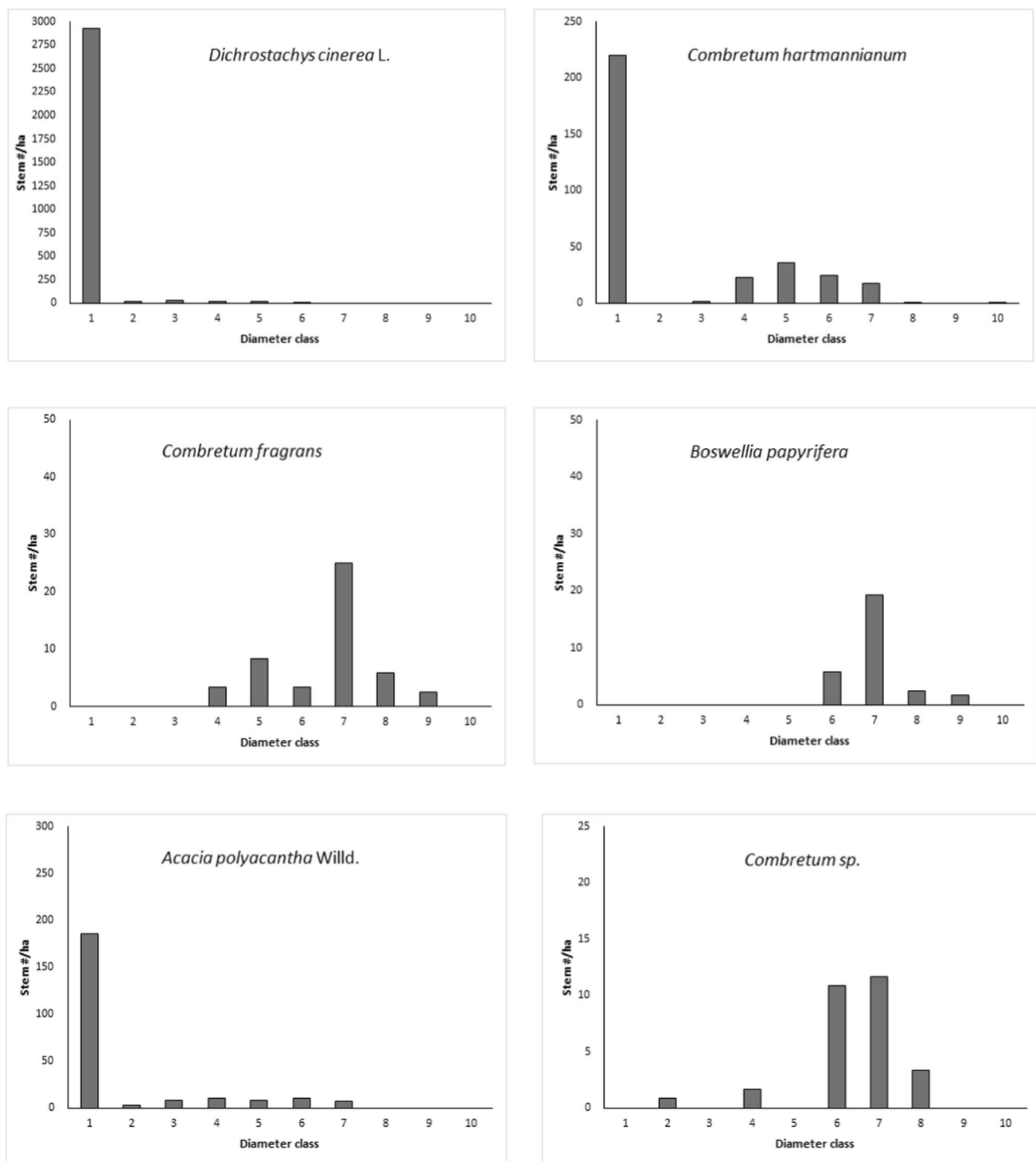


Fig. 3 Population structure of selected dominant woody species recorded at Waldiba monastery woodland. Stem diameter classes are (in cm): (1) DBH < 2, (2) ≥ 2 DBH < 4, (3) ≥ 4 DBH < 6, (4) ≥ 6 DBH < 8, (5) ≥ 8 DBH < 10, (6) ≥ 10 DBH < 20, (7) ≥ 20 DBH < 30, (8) ≥ 30 DBH < 40, (9) ≥ 40 DBH < 50, and (10) DBH > 50

3.1.6 Importance value index (IVI)

The most ecologically important species in the woodland (Table 1) with IVI value of more than 50 were *D. cinerea*, *C. fragrans*, *Combretum sp.*, and *C. hartmannianum*. The three economically important tree species in the woodland, *B.*

papyrifera, *V. polyacantha* and *Sterculia africana*, had IVI values > 10.77. Around 80% of the species in the forest have IVI of more than 5, indicating that the woodland is composed of ecologically important woody species.

Tamarindus indica, *Cissus petiolata*, *Commiphora africana*, *Diospyros mesphiliformis*, *G. flavescens*, *Z. spina-christ* and *Ostostegia fruticosa* are species with IVI value of < 5%, and therefore need immediate conservation intervention. Moreover, there are indigenous plants that are listed in the IUCN red list that need special attention and conservation action.

3.1.7 Population structure

The selected woody species demonstrated various patterns of population structure (Fig. 3), implying different population dynamics of each species. Only *D. cinerea* demonstrated a normal (inverted J shape) population growth pattern with good reproduction and recruitment capacity. The others showed either bell-shaped, J-shaped or irregular growth patterns with missing diameter classes in either the lower, upper or middle diameters. For instance, *B. papyrifera* showed a hampered seedling, sapling and shrub recruitment and a very low stocking in the upper diameter class (2 stems/ha), implying the high level of a threat to the species due to its limited recruitment capacity.

3.1.8 Regeneration status

The distribution of seedlings, saplings and mature trees/shrubs in Waldiba dry woodland showed three distinct patterns. The first group (of good regeneration) included species represented by all three stages and included *V. polyacantha*, *C. hartmannianum* and *D. cinerea*. The second group (poor regeneration) is represented by seedling and mature trees/shrubs but not by saplings and includes *D. melanoxylon*, *D. abyssinica*, *T. brownii* and *X. americana*. The third group (of fair regeneration) was represented by sapling and mature trees/shrub but not seedlings, and comprised *G. ferruginea* and *J. floribundum*.

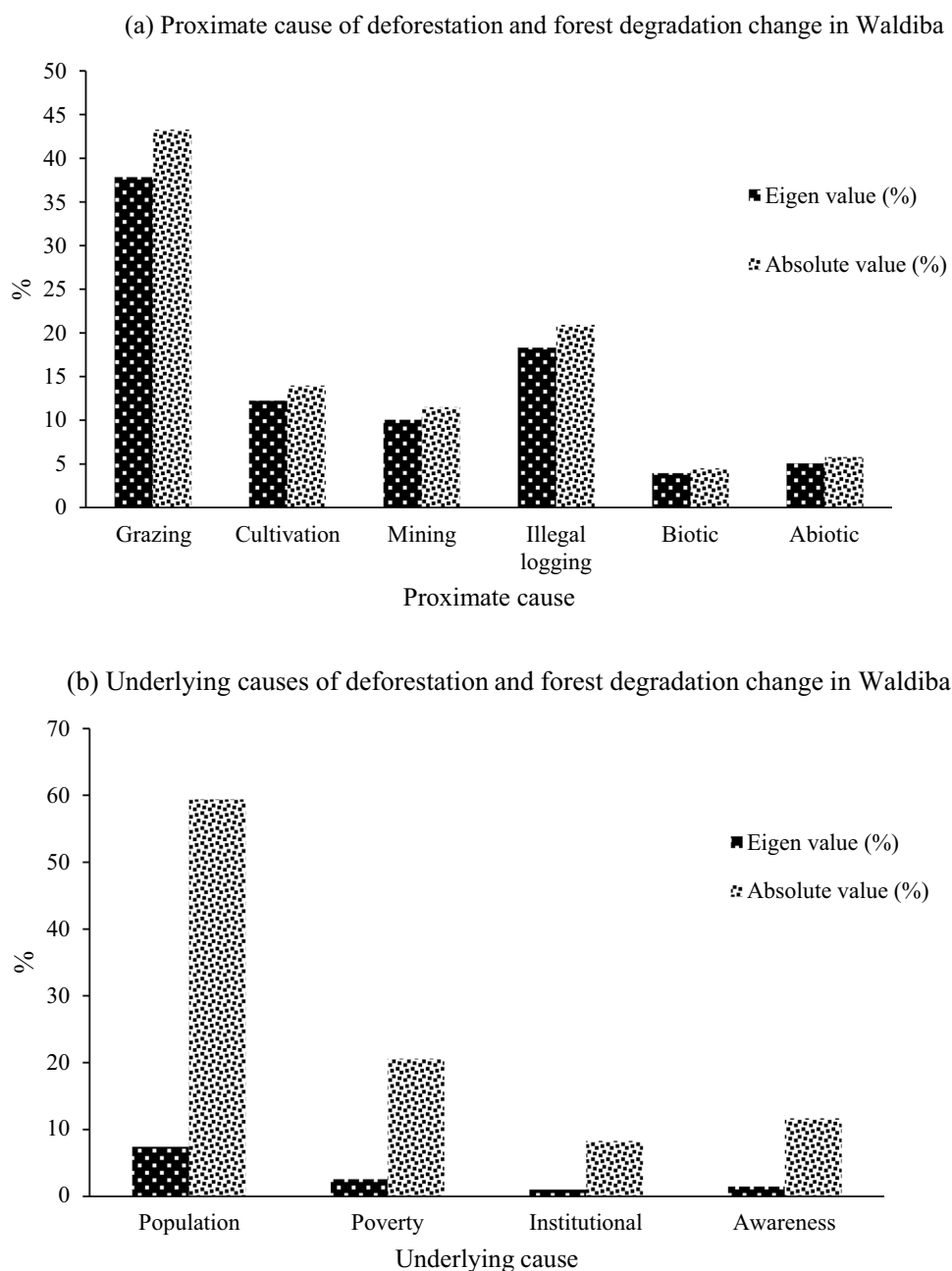
3.2 Drivers of deforestation and forest degradation in Waldiba dry woodland

The informants noticed that the forest cover dwindled and declared that both the proximate (87.50%) and underlying (12.5%) causes were the main reasons for the forest cover change (Figs. 4a and 5). Uncontrolled grazing, illegal logging, cropland expansion, mining, biotic and abiotic factors were the main proximate drivers of forest cover change (Figs. 4b and 5). Whereas, population increase, poverty, lack of awareness and institutional (policy) issues with their respective weighted value of 7.43%, 2.57%, 1.46% and 1.04%, respectively, were the main underlying causes for cover change.

Uncontrolled/free livestock grazing is a proximate driver that needs much attention, as it could also be the underlying cause of other forms of degradation. Cattle from nearby villages in Asgede Tsimbla, Tselemti, Sheraro and Tsegede districts of the woodland and distant districts, such as Inticho (~ 235 km away) and previously Mendefera in Eritrea, are brought to Waldiba for grazing. During the rainy season, the livestock browse in the woodland. However, during the dry season the herders cut tree branches to feed their livestock. In most cases, they do not do proper lopping, but rather they cut the trees at some point above the ground that might be difficult for the tree to rejuvenate or regrow. The mass movement of livestock in certain locations has also impacted the regeneration of the flagship tree species—*B. papyrifera* and *A. digitata*. Furthermore, herders cut for firewood trees that have good calorific value and less smoke. There is less tendency of using dead trees that are present in the woodland. When the herders fall short of ranching areas, they also burn the woodland to obtain space for their animals and to construct dwellings for themselves.

The other major stakeholders who are drivers of forest degradation (land use change) are gold miners, monks of the monastery, tappers and poachers. For traditional gold mining, vast area of the woodland has been destroyed. Moreover, the gold miners and the tappers use wood and wood products for making utensils, digging and tapping material, shelter construction, cooking and heating. Likewise, due to lack of awareness, monks are also involved in logging of trees for fuelwood and construction poles. Worse still, they increasingly cut quality stands of rare and valuable trees like *Combretum* sp. to construct shelter. Wood of the species is hardy in nature and resistant to termite attack. The poachers are involved in biodiversity loss through the hunting of wildlife apart from the use of fuel wood and poles, all of which was further affirmed by the KII. As a result of poaching for bush meat, many wildlife such as Minilik bushbuck and other antelope that used to occur in the woodland have been lost or are greatly reduced in numbers.

Fig. 4 Proximate (a) and underlying (b) causes of deforestation and forest degradation in Waldiba dry woodland



4 Discussion

4.1 Floristic composition, diversity and community types

Floristic composition of a vegetation can be described in terms of species richness, abundance, dominance, and frequency [48, 53]. In this study, a total of 39 indigenous woods species including trees, shrubs and lianas were recorded. The *Combretaceae* and the *Fabaceae* were the dominant families. The dominance of the *Combretaceae* and the *Fabaceae* in the present study is in line with what has been reported for Dambos ecosystems in northern Mozambique [54] and Eastern Ghats of Andhra Pradesh [55]. Similarly, the *Combretaceae* and the *Fabaceae* were reported to be the most species rich families in the woodlands of Hirmi [37], Kafta-Sheraro National Park [35], Metema [48], Xobe, Island Safari and Shorobe [43], Xobe and Shorobe [42] and Mopane [46].

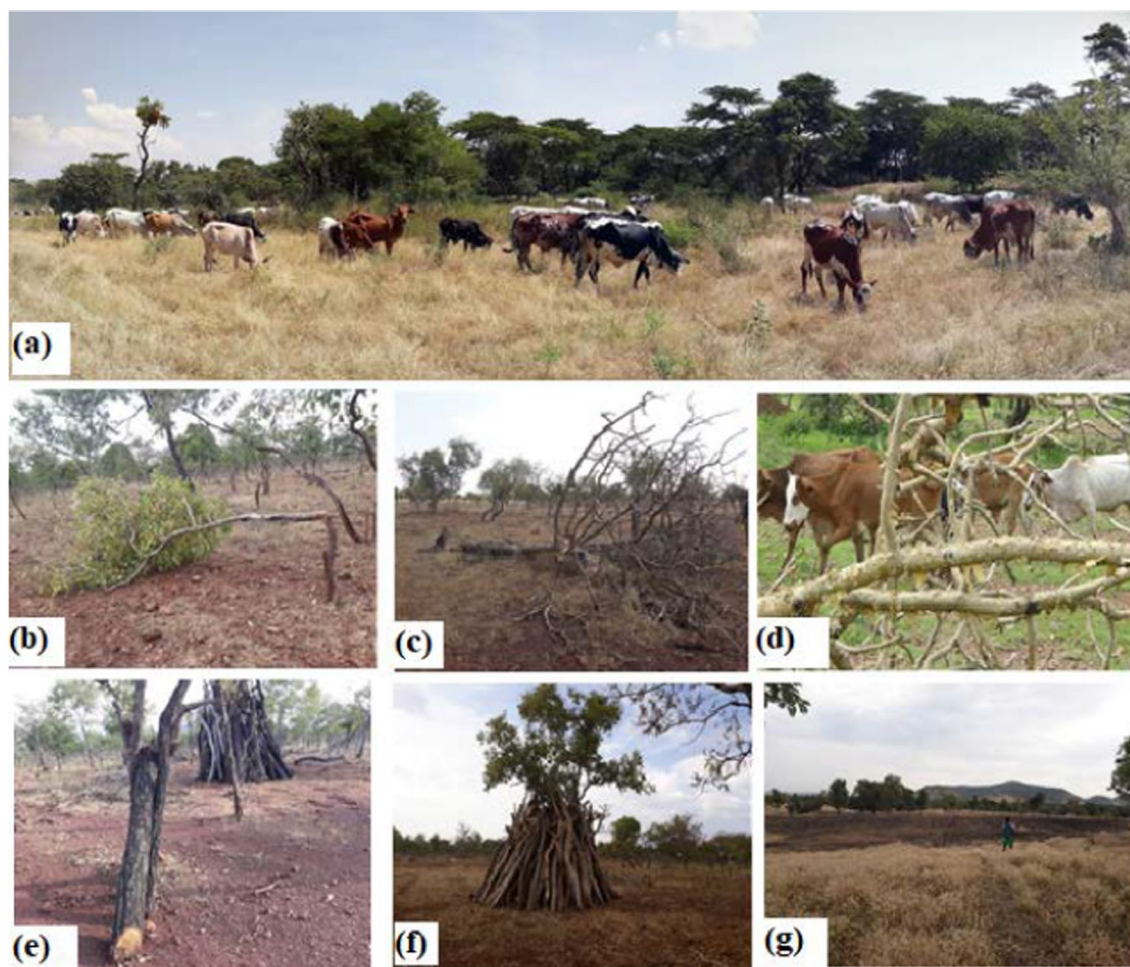


Fig. 5 Drivers of forest cover change in Waldiba **a** uncontrolled grazing, **b** a tree cut for goat browse, **c** tree dieback, **d** a dead *B. papyrifera* tree because of attack by the long horn beetle, **e** newly cut logs of *Combretum* sp. **f** wood cut for fuelwood and construction poles, and **g** grassland burnt for expansion of land for cultivation

In Ethiopia, the family Fabaceae is the most species rich family with 678 species [35, 56] while *Combretaceae* is common woodland species [35, 37, 42, 43, 46, 48, 57]. The dominance of these two families could be attributed to their efficient pollination and successful seed dispersal mechanisms [35]. Furthermore, the leguminous species contains drought tolerant, deciduous, nitrogen fixing and spiny species that are well adapted to the prevailing drought conditions [29, 35] of dry woodlands.

Patterns of species community are associated with environmental factors like climate, topography (slope, aspect, altitude), soil as well as anthropogenic and livestock disturbances [37]. In the present study, three plant community types were identified from the agglomerative hierarchical cluster analysis. This is far lower than those reported for Hirmi [37] due to the low altitudinal variation in the present study.

Factors like anthropogenic and environmental influences have a strong impact on species richness, forest structure and composition [53]. The species richness of the woodland is comparable to that reported for Metema [48], Xobe and Shorobe [42, 43], and Mopane [46] but slightly lower than that reported for Kafta-Sheraro National Park [35] and Hirmi woodland [37], which have the same ecological setting.

Species diversity is the most often used depiction of ecological diversity [58]. The relatively high diversity and evenness indices indicate the need to conserve the floristic diversity of the study site and protect the woody vegetation from human disturbances [52]. The Shannon diversity values recorded in the present study were higher than those reported for Gera woodland in Abergele [18], South Nandi forest in Kenya [32], Kafta Sheraro National Park [35], Mopane woodlands [46], islands of Lake Ziway [36], Tara Gedam and Abeyaye forests [52], Xobe and Shorobe [42], Island Safari, Shorobe and Xobe [43], Kumorakata Reserve Forest and the Hojai Reserve Forest [59] and lower than those reported for Hirmi [37],

Metema [48], Ryukyu Archipelago [60] and Eastern Ghats [55]. Likewise, the evenness is comparable with that reported in other studies conducted on other dry woodlands [42, 43, 46].

The most frequent species were *D. cinerea*, followed by *C. fragrans*, then *C. hartmannianum*, *Combretum* sp., and *Z. abyssinica*. The relative frequency of a species reflects the pattern of distribution and provides an approximate indication of the heterogeneity of a stand [36, 48, 52]. Thus, the high frequency of the species could be the result of a wide adaptability range and dispersal mechanisms [51].

Basal area is used to explain the crowdedness of a stand of natural vegetation (Table 1). A stand of large trees is more crowded than one with the same number of trees of smaller diameter [29]. The total basal area of the forest in the present study was $49.27 \text{ m}^2 \text{ ha}^{-1}$ which is greater than the expected range of basal area of $23\text{--}37 \text{ m}^2 \text{ ha}^{-1}$ for virgin tropical forests. The species with the largest basal area was *B. papyrifera*, possibly due to its big size [52], followed by *C. fragrans*, *Combretum* sp., *C. hartmannianum*, *Terminalia brownie* and *V. polyacantha*. Thus, these species are considered the most ecologically important species and the difference in basal area could be due to the presence of old growth and big diameter trees. The basal area of the woodland was greater than that of Hirimi [37], Metema [48], South Nandi forest [32], Zengena Forest [61] and Eastern Ghats of Andhra Pradesh [55], comparable with that of Ishigaki forest [60], Abebaye forest [52], and less than that of Okinawa forest [60], Tara Gedam [52], Kumorakata Reserve Forest [59] and islands of Lake Ziway [36].

The total density of mature woody plants in the present study was $922 \text{ stems ha}^{-1}$. This value is higher than those reported for other similar woodlands like Hirimi [37], Galilla, Debre Sina, Tullu Guddo, Funduro and Tsedacha [36] Eastern Ghats of Andhra Pradesh [55] and Metema [48] and lower than those reported for Tara Gedam and Abebaye [52]. These differences in density could be attributed to the variation in natural regeneration and dispersal patterns of the species, the inability/ability of individuals to withstand the harsh environmental conditions (low rainfall regime, high temperature), disturbance degree, livestock trampling and grazing, other biotic and abiotic factors [48].

Species with the highest dominance indices might be considered the most important species in the studied woodland [48]. The IVI is an important parameter that expresses the structural importance or ecological significance of species in a given ecosystem [32, 45, 48, 52, 62]. Species with high IVI values are considered more important than those with low IVI values. Likewise, IVI can be used to prioritize species for conservation. Species with lower IVI values need high conservation efforts while those with higher IVI values need monitoring [45] and less conservation effort [52]. The IVI value of the present study is higher than those of other similar woodlands like Hirimi [37], Metema [48], islands of Lake Ziway [36], Tara Gedam [52], Komto forest [45], Island Safari, Shorobe and Xobe [43] and Shorobe [42]; comparable with those of Xobe [42] and Mopane woodland [46]; and lower than those of Abebaye forest [52].

In the absence of long-term demographic data of the species populations, the use of diameter class distributions of woody species from a single survey has been shown to be a potential and reliable tool for revealing population dynamics and recruitment of woody species [42, 45]. It is also used to predict responses of the a species to disturbance, to its environment and to the resultant changes in population structure [42, 45, 48]. In the present study, the population structure exhibited various patterns. To this end, several researchers have argued that species like *B. papyrifera* are facing extinction [63, 64], and have proposed that they should be included in the “vulnerable” threat category of the IUCN red list [65]. Thus, the species that show irregular population growth patterns should be considered for conservation intervention [51]. Similar findings were reported for other woodlands [36, 37, 42, 43, 48, 51, 52].

Regeneration is a central component of tropical forest ecosystem dynamics and management, conservation and restoration of degraded woodlands. Sustainable forest utilization is possible only if adequate information on regeneration dynamics and the factors influencing important canopy tree species is available [66]. The composition, distribution and density of seedlings and saplings are indicators of the future regeneration status of any woodland [45]. Such deforestation and forest degradation in church forests and woodlands were reported elsewhere in Ethiopia [13, 14, 67]. Consistent with the findings of present study, the impact of transhumance on vegetation has been acknowledged in Ethiopia [68, 69], and other parts of the world [70, 71].

5 Conclusion

Floristic composition results revealed that the study site harboured 39 woody species with high levels of nativity, species richness and diversity with more or less even distribution and less dominance. The regeneration status was not promising for the vast majority of the species. Species with low IVI values, hampered recruitment, vulnerable species, flagship species, rare, threatened and endangered species should be prioritized for in situ and ex situ conservation intervention.

Whereas in the study area, both proximate (87.50%) and underlying (12.50%) causes played a pivotal role in driving the forest cover dynamics with more than 76% of the cover change occurring due to overgrazing-induced illegal logging and farmland expansion. As such, introducing participatory forest management is crucial for reducing anthropogenic pressure and ensuring the woodland's conservation, management, and sustainable use. Furthermore, as the woodland should be managed for ecosystem service and biodiversity conservation, research on the soil seed bank, regeneration, population dynamics, biology and reproductive ecology (pollination, seed production, dispersal and germination) of native and endemic species is imperative.

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Author contributions DBH & AN: Conception and design of the research, data collection, data analysis and interpretation, drafting and revising the manuscript. EB, ANR, AST, TG, KMH & KG: data analysis and interpretation, drafting and revising the manuscript.

Data availability The data used to support the findings of this study are included in the manuscript.

Declarations

Competing interests The authors declare no competing interests.

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