Bioscene

Bioscene
Volume- 21 Number- 02
ISSN: 1539-2422 (P) 2055-1583 (O)
www.explorebioscene.com

Islamic Sacred Groves: Ecological Niches of Plant Diversity and Climate Change Mitigation in Northern Ethiopia

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Abstract: Islamic sacred groves represent critical ecological niches, fostering diverse habitats for plants and animals. Despite their ecological significance, safeguarding these areas presents formidable challenges stemming from multifaceted factors. Consequently, our study examines plant diversity, biomass and carbon stock estimation in eight Islamic cultural centers in northern Ethiopia. The data were collected from sixty-three plots: 20×20 m for trees, 5×5 m for shrubs, and five 1×1 m subplots within each main plot.We identified 204 plant species belonging to 144 genera and 66 families. The Asteraceae family emerged as dominant, comprising 17 species accounting for 15.3% of the total species identified. Herbs were the predominant growth form, constituting 102 species (50.2%), followed by shrubs (48 species, 23.7%), trees (43 species, 21.2%), and climbers (10 species, 4.9%). Thirteen endemic plant species were identified, while six indigenous tree species predominantly populated the sites. The altitude and slope significantly influenced the plant species distribution patterns. The total biomass of the stud sites ranged from 12.2 to 283 tons per hectare, contributing 6.1 to 141.5 tons of carbon per hectare. The exhibited CO_2 sequestration potential ranged from 17.7 to 408.8 tons per hectare. The study sitesserve as repositories of plant genetics, essential for conserving biodiversity and providing germplasm for restoration initiatives. Moreover, they play a crucial role in mitigating climate change impacts in northern Ethiopia.

Keywords: Carbon, Conservation, Diversity, Forest, Patch, Sacred Groves.

Introduction

Forests are not equally distributed throughout the globe and cover only 31% of the total area (FAO, 2020). Ethiopia has a diverse range of forests, which play a crucial role in the country's ecology, economy, and cultural heritage. The country is home to several hotspots for biodiversity in East Africa (Fashing et al., 2022). It is also one of the East African regions of global significance for the conservation of biodiversity (Olson and Dinerstein, 2002). The plant resources of the country include 6,027 plant species (Sebsebe et al., 2021). Its varied climate and geological history are linked to the development of its vegetation (Mengesha et al., 2020). The forests of Ethiopia are under pressure due to deforestation, population growth, overgrazing, and agricultural expansion (Badege Bishaw, 2001; Alemayehu Wassie, 2007; Ermias Aynekulu, 2011). As a result, the forest cover was above 40% at one time, then decreased to 2.8%, and is currently reaching 15.12% (FAO, 2020). The remaining natural forests of Ethiopia are primarily found in the southern and southwestern regions, with a few scattered areas remaining in the northern, central, and eastern regions (Getahun and Anteneh, 2015). Forests in the northern part of the country, particularly the Amhara region, are concentrated in state forests, parks, inaccessible hillsides, churches, and mosques (Alemayehu Wassie, 2010; Reynolds et al., 2016; Birhan and Solomon, 2020).

Islamic sacred groves in northern Ethiopia are forest patchesthat survive as a result of the traditional conservation efforts of some individuals and the community. These sites are significant carbon sinks, sequestering atmospheric carbon dioxide and storing it in the form of biomass. Recently, carbon storage and sequestration in forests and forest patches have become significant concerns for climate change mitigation and maintaining the balance of greenhouse gases in the atmosphere (Chen et al., 2021; Melese and Belachew, 2022). According to Moges et al. (2010), the forest resources in Ethiopia comprise approximately 2.76 billion tons of carbon. Mekonnen and Tolera (2019) reported that dry afromontane forests in Ethiopia store a significant amount of aboveground carbon compared to other terrestrial ecosystems.Thus, forest patches within Islamic sacred groves make a significant contribution to the northern parts of Ethiopia. Accordingly, studies on floristic composition and carbon estimation in forest patches are particularly relevant to ongoing environmental changes, including land use conversion, deforestation, and climate variability (Ermias Aynekulu, 2011). As forest patches face increasing threats from human activities and natural disturbances, it is crucial to evaluate their ecological integrity and carbon storage capacity. Furthermore, understanding the relationship between floristic composition and carbon storage in forest patches can provide valuable insights into the mechanisms driving ecosystem functioning and resilience in the face of environmental change.

However, the plant diversity and carbon storage potential of forest patches, particularly in Islamic sacred groves (i.e., mosques, hujibs, dorih, and traditional Islamic schools, "mediresa"), and graveyards have not been studied. In this study, we aimed to investigate floristic diversity and carbon storage in forest patches within Islamic sacred groves (ISGs) in Wollo. By conducting field surveys and employing established methods for quantifying plant species and estimating biomass, we seek to characterize plant species and assess their carbon storage potential. Through this research, we aim to contribute to the broader understanding of biodiversity conservation and carbon sequestration in forest ecosystems in the ISG, with implications for the sustainable management of forest patches in the ISG and climate change mitigation efforts.

Materials and Methods

Description of the Study Areas

The research sites were located in Wollo in the Amhara region, which had a boundless impact on the dissemination of Islamic knowledge in Ethiopia. Sites were selected based on their historical and religious significance, concern for biodiversity conservation, and vegetation cover. This species is primarily found in the towns of Mersa and Dessie, as well as Kalu, Dessie Zuriya, and TehuledereWoreda. The specific Islamic cultural centers included the Haik Central Mosque (11°18'54.39"N, 39°40'40.75"E), Geta (10°59'43.33"N, 39°46'58.44"E), Bilen (11°5'40.73"N, 39°36'50.59"E), Beke Meda (11°0'30.40"N, 39°48'50.62"E), Mejit (11°5'53.44"N, 39°45'22.79"E), Kurkur (10°58'43.25"N, 39°43'8.05"E), Mersa (11°39'49.58"N, 39°39'53.37"E), and Ardibo (11°11'56.06"N, 39°45'37.83"E), as indicated in Figure 1. The climate data were obtained from representative and nearest meteorological stations located in Kombolcha, Dessie, Haik, and Mersa towns. The study sites exhibited an annual rainfall of 930–1186 mm and an annual temperature range of 16–21 °C. The study sites are covered by different flora diversity.

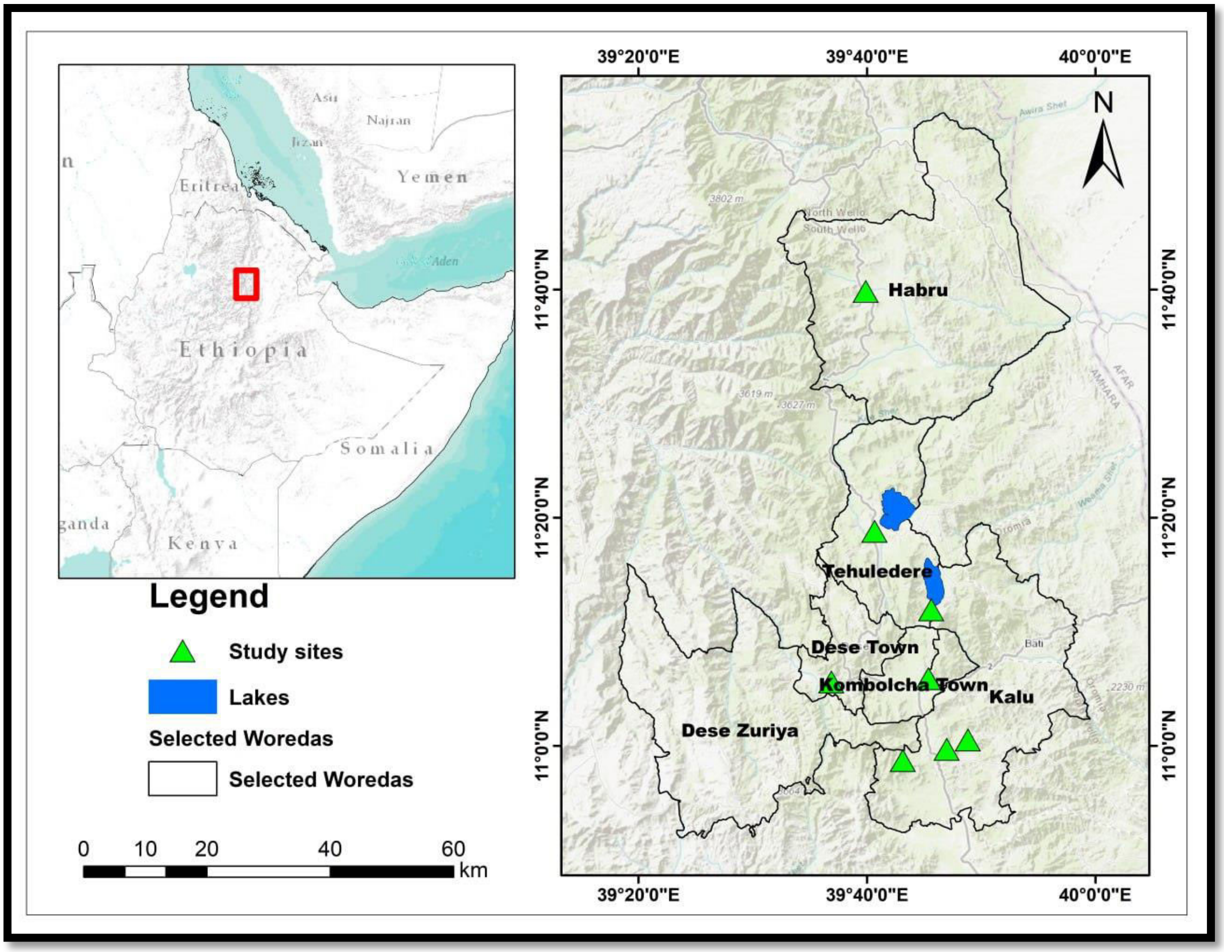

Figure 1: Location map of the study sites.

Methodology

Sampling Design and Vegetation Data Collection

A systematic random sampling technique was employed to collect data on floristic composition, structure, diversity, and species richness. The transect lines were positioned 50 meters from one another. A total of 63 plots with a size of 20 × 20 meters were used and spaced 50 m apart between the plots for collecting floristic and structural data on trees; 5 × 5 m in the middle were used for shrubs; and five 1 × 1 m subplots, one at the center and four at each corner of the main sampling plot, were used to count the herbs.

Woody plants >2 m in height and >2 cm in diameter at breast height (DBH) were counted and measured in each sample plot and subplot for structural analysis. For trees or shrubs that branched at breast height or below, the diameter of each branch was measured separately, and the average was taken. The circumferences of the woody plants at breast height (approximately 1.3 m) were measured using a tree caliper and DBH tape. In each sample plot, cover and abundance values for all woody species were visually evaluated and converted to the Braun-Blanquet scale as modified by van der Maarel (1979). Slope and aspect were measured using a compass, while altitude and geographic coordinates were determined using a Garmin 62 GPS. The growth of the plants was recorded, and voucher specimens were collected. Voucher specimens were collected and identified at the National Herbarium (ETH) at Addis Ababa University. The identification of specimens was performed both in the field and later at ETH using taxonomic keys in the Flora of Ethiopia and Eritrea and by comparison with authenticated herbarium specimens. The nomenclature of the plant specimens followed the floras of Ethiopia and Eritrea.

Plant Diversity Analysis

To assess the diversity of plant species, the Shannon–Wiener diversity index (H) and evenness index (J) were computed. It accounts for both the abundance and evenness of the species present.

The Shannon diversity index can be calculated by Eq. (1) as follows:

$$H' = \sum_{i=1}^{s} \mathrm{Pi} \ln \mathrm{Pi} \qquad (1)$$

where H' is the Shannon diversity index, pi is the proportion of individuals found in the i^{th} species, and ln is the natural logarithm of base e (loge).

The evenness index (J) was calculated to estimate the homogeneous distribution of tree species on the forest patches of the Islamic sacred groves. It was computed by Eq. (2) as follows:

$$J = \frac{H'}{H'max} \qquad (2)$$

where H' = Shannon–Wiener diversity index and H'max = ln s, where s is the number of species.

The floristic dissimilarity between all pairs of patches was computed using beta (β) diversity following Whittaker (1972).

Estimation of above- and belowground biomass and carbon stock

The carbon stock of each forest patch in the Islamic sacred groves was estimated through a nondestructive approach involving the use of allometric equations (Yilma and Derero, 2020). The biomass of each tree was calculated using the same allometric equation because many species do not have a species-specific allometric equation (Cardelus et al., 2019), and this approach consumes time and money. Therefore, according to Chave et al. (2014),ageneral allometric equation was used to determine the biomass of woody species with a DBH ≥5 cm because it accords with the biophysical conditions of the study area (Yilma and Derero, 2020; Esubalew et al., 2019). The carbon stock of each Islamic sacred site was estimated following Chave et al. (2014), as indicated in Eq. (3).

$$AGB = 0.0673 * (\rho D^2 H)^{0.976} \qquad (3)$$

where AGB=aboveground biomass (kg), H=tree height (m), D=diameter (cm) at breast height (1.3 m), and ρ=wood density (ton/m^3) (0.58 ton/$m^{3)}$ (Esubalew et al., 2019).

The biomass of woody species was converted into carbon (C) following Brown (2002), as indicated in Eq. (4). The CO_2 equivalent sequestered in the aboveground biomass = AGC * 3.67 (Pearson et al., 2007).

$$AGC = AGB * 0.5 \quad (4)$$

where AGC=aboveground carbon.

Estimation of belowground biomass is much more difficult and time consuming due to the uncertainty of root biomass measurements. Root biomass is often estimated from root-shoot ratios using reports from the IPCC (2003) for dry forests, as shown in Eq. (5).

$$BGB = AGB * 0.27 \quad (5)$$

$$BGC = BGB * 0.5 \quad (6)$$

where BGC = below ground carbon.

BGB = belowground biomass.

Then, the total biomass carbon stock was calculated by Eq. (7):

followingthe formula of Pearson et al. (2005).

$$TBC = AGC + BGC \quad (7)$$

where TBC = total biomass carbon stock (ton/ha).

Vegetation analysis and graphing were performed using the free statistical software environment R, version 3.5.0 (R Core Team, 2022). Tables were analyzed using Microsoft Excel.

Results

Floristic Composition

The study revealed 204 plant species comprising 144 genera and 66 families (see supplementary 1). Among these, 200 angiosperms (i.e., 11 monocotyledons and 189 dicotyledons), 3 gymnosperms and one pteridophyte family were verified. The greatest number of species was recorded at the Geta site (111 species), and the lowest number (34 species) was recorded at the Ardibo site (Table 1).

Table 1: Number of species, genera and families in the studied forest patches

Study Sites	Number of Plots	Altitudinal range (m)	Species	Genus	Families
Ardibo	4	2135-2143	34	33	19
Beke Meda	4	1944-1964	35	32	22
Bilen	9	2274-2369	85	69	38
Geta	14	2093-2145	111	87	48
Haik	9	2003-2030	72	62	35
Kurkur	4	2104-2121	58	54	32
Mejit	7	2024-2074	57	52	27
Mersa	12	1573-1585	46	40	25
Overall	63	1573-2369	204	144	66

In the studied forest patches, there were 1 to 17 different species per family. The Asteraceae family was dominant, contributing 17 species (15.3%) in Geta, 14 species (16.47%) in Bilen, 9 species (15.79%) in Mejit, 8 species (11.11%) in Haik, 6 species (10.34%) in Kurkur, 4 species (11.43%) in Beke Meda, 3 species (8.82%) in Ardibo and 2 species (4.35%) in the Mersa sites. The second most dominant family was Poaceae, which contributed 9 species (8.1% in Geta and 10.59% in Bilen, followed by 8 species (14.04%) in Mejit, 7 species (9.72%) in Haik, 5 species (10.87%) in Mersa, 4 species (11.43% and 6.89%) in Beke Meda and Kurkur, respectively, and three species (8.82%) in Ardibo. Fabaceae also contributed 9 species (8.1%) to Geta, 6 species (8.33% and 13.04%) to Haik and Mersa, respectively, 5 species (5.88% and 8.77%) to Bilen and Mejit, 4 species (6.89%) to Kurkur, 3 species (8.82%) to Ardibo and two species (5.71%) to Beke Meda. Lamiaceaecontributed 9 species (8.1%) at the Geta site, 7 species (8.2%) at the Bilen site, 6 species (10.34%) at the Kurkur site, 4 species (7.01%) at the Mejit site, 3 species (4.2%, 6.5%) at the Haik and Mersa sites, and 2 species (5.7%, 5.9%) at the Beke Meda and Ardibo sites. The family Acanthaceaeshares 5 species (4.5%) in Geta and 4 species (11.8%, 5.6%, and 7%) in Beke Meda, Haik, and Mejit, respectively. It also contributed three species (6.5%, 5.2%, 35% and 8.8%) to Mersa, Kurkur, Bilen and Ardibo, respectively. Euphorbiaceaecontributed 4 species (11.8%, 3.6%, 5.6% and 8.7%) at the Ardibo, Geta, Haik, and Mersa sites, respectively; two species (%) at the Mejit site; and one species (1.2%, 2.9% and 1.7%) at the Bilen, Beke Meda and Kurkur sites, respectively.Malvaceaecontributed 4 species (%) in Mejit, 3 species (4.2%) in Haik, two species (2.4%, 1.8%) in Bilen and Geta, and one species (2.9%, 2.2%) each in Ardibo and Mersa. The remaining families in the forest patches included one to two species (Figure 2).

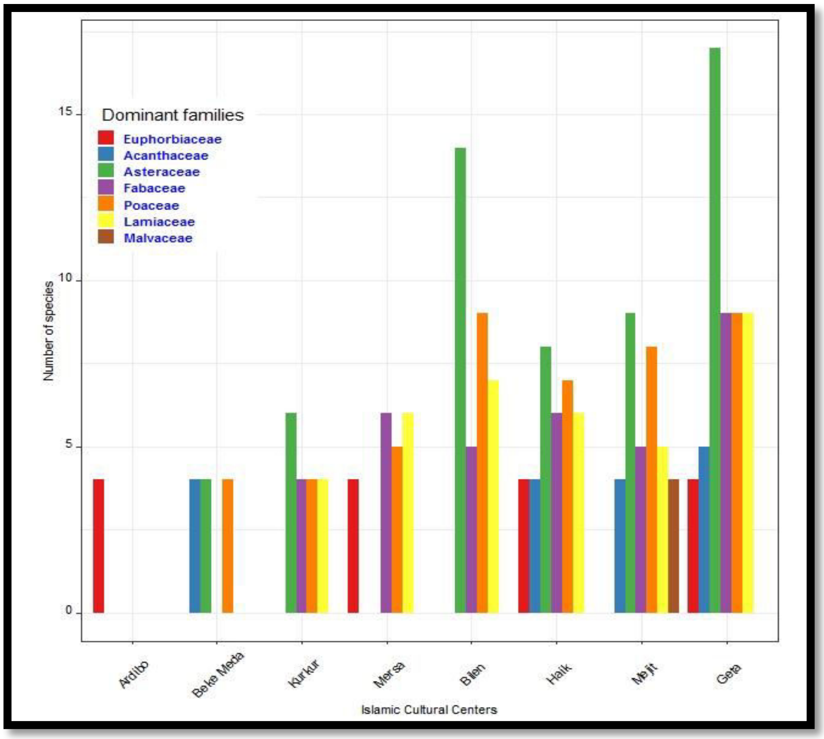

Figure 2: Contribution of dominant families in the studied forest patches.

In the studied forest patches, Geta was dominant in herbs (57.8%) and shrubs (26.6%), followed by Bilen, Mejit, Ardibo, Haik, Beke Meda, Kurkur, and Mersa. Haik was dominant among the trees (24.66%), followed by Mersa (34.78%), and the lowest percentage was recorded for Beke Meda (14.29%) (Table 2). However, the overall study confirmed that herbs composed 102 species (50.2%) of the eight forest patches, followed by shrubs (48 species, 23.7%), trees (43 species, 21.2%), and climbers (10 species, 4.9%) (Table 2).

Table 2: Habit distribution in different forest patches.

No	**Islamic Cultural Centers**	**Habit of the plant species**							
		Climbers		Herbs		Shrubs		Trees	
		Species	%	Species	%	Species	%	Species	%
1	Geta	3	2.75	63	57.8	29	26.6	14	12.8
2	Mersa	2	4.35	18	39.13	10	21.74	16	34.78
3	Beke Meda	1	2.86	16	45.71	13	37.14	5	14.29
4	Mejit	3	5.26	29	50.88	13	22.81	12	21.05
5	Kurkur	4	6.89	25	43.10	18	31.03	11	18.97
6	Bilen	5	6.02	48	57.83	23	27.71	7	8.43
7	Haik	5	6.85	35	47.95	15	20.55	18	24.66

8	Ardibo	1	2.94	16	47.05	9	26.47	8	23.53
Overall		10	4.9	102	50.20	48	23.7	43	21.2

However, 13 (6.4%) species are endemic to Ethiopia and Eritrea. Seven shrub species, five herb species, and two tree species constitute the total number of endemics (Table 3). The Asteraceae, which comprises four endemic species, was the most diversified family, followed by the Aloaceae, which contributed two species, and each remaining family contributed one species.

Table 3.Endemic plant species in the studied Islamic cultural centers.

Name of endemic species	**Family**	**Habit**	**IUCN category**
Aloe debrana	Aloaceae	Herb	
Aloe weloensis	Aloaceae	Herb	
Echinopskebericho	Asteraceae	Shrub	
Echinopslongisetus	Asteraceae	Shrub	LC
Jasminumstans	Oleaceae	Shrub	
Kalanchoepetitiana	Crassulaceae	Herb	
Lippiaadoensisvar.adoensis	Verbenaceae	Shrub	LC
Maytenusaddat	Celastraceae	Shrub	NT
Millettiaferruginea	Fabaceae	Tree	LC
Phagnalonabyssinicum	Asteraceae	Herb	
Rhusglutinosasubsp.glutinosa	Anacardiaceae	Tree	VU
Thymus schimperi	Lamiaceae	Herb	
Vernonialeopoldii	Asteraceae	Shrub	LC

Species diversity

The alpha diversity of the forest patches ranged from 3.2-4.2, and the mean evenness value ranged from 0.96. The highest Shannon–Wiener diversity index and evenness values of 4.26 and 0.98, respectively, were found at the Geta site, and the lowest were found at the Ardibo site. For both indices,a higher value indicates more diversified sites (Table 4).

Table 4.Species diversity and evenness of the studied forest patches.

Study Sites	Shannon Diversity Index	Simpson's Diversity Index
Ardibo	3.153524	0.9420552
Beke Meda	3.303489	0.9506357
Bilen	4.017711	0.9743553
Geta	4.258726	0.9790567
Haik	3.889287	0.9721771
Kurkur	3.786139	0.9702623

Mejit	3.660567	0.9641129
Mersa	3.483775	0.9611474

Comparison of species composition among sites

Beta diversity was lowest in the forest patches with the greatest similarity and highest in the patches with the lowest similarity. The beta diversity between the forest patches in Beke Meda and Kurkur (0.55) and Haik and Mejit (0.58) indicated that these patches had relatively similar species compositions. This could be due to the similar altitudinal ranges of the forest patches. The beta diversity between the forest patches in Bilen and Mersa (0.88) and Kurkur and Mersa (0.83) was less similar in terms of species composition. This can be associated with the difference in altitudinal range. Ardibo and Haik, however, had significantly greater pairwise similarity scores (0.72) than did the majority of the other forests. These two patches exhibit characteristics that are typical of other forests (Table 5). The forest patch of Geta (which had the highest species diversity) shared the most species with the Haik, Bilen, Mejit and Kurkur forest patches and the fewest species with the Mersa, Beke Meda, and Ardibo forest patches.

Table 5: Beta diversity indices of the studied forest patches.

	Ardibo	Beke Meda	Bilen	Geta	Haik	Kurkur	Mejit	Mersa
Ardibo	0.00							
Beke Meda	0.68	0.00						
Bilen	0.74	0.73	0.00					
Geta	0.80	0.76	0.61	0.00				
Haik	0.72	0.65	0.63	0.61	0.00			
Kurkur	0.76	0.55	0.59	0.68	0.68	0.00		
Mejit	0.64	0.61	0.74	0.63	0.58	0.69	0.00	
Mersa	0.74	0.74	0.88	0.76	0.67	0.83	0.65	0.00

Ordination

The results from the CCA showed the following relationships between sites and environmental conditions. The variable with the greatest impact on species composition was altitude, as indicated by the longest arrow. CCA1 reflects gradients of aspect and human impact. Along CCA1, human influences were found to be quite strong at the Mersa and Mejit sites. According to CCA2 of the ordination diagram, species presence is determined by altitude, livestock grazing, and slope, with a focus mainly on the Geta, Bilen, and Kurkur sites. Along CCA2, the differentiation is based on altitude and is mainly found at the Bilen and Kurkur sites. However, the effects of slope and livestock grazing were also statistically significant and were commonly found at the Geta site. Two sites (i.e., Ardibo and Beke Meda) were protected through community social rules from human and grazing factors, and the Haik mosque was fenced well and protected by the community since it is used as a grave yard; these factors are not significant for the site (Figure 4).

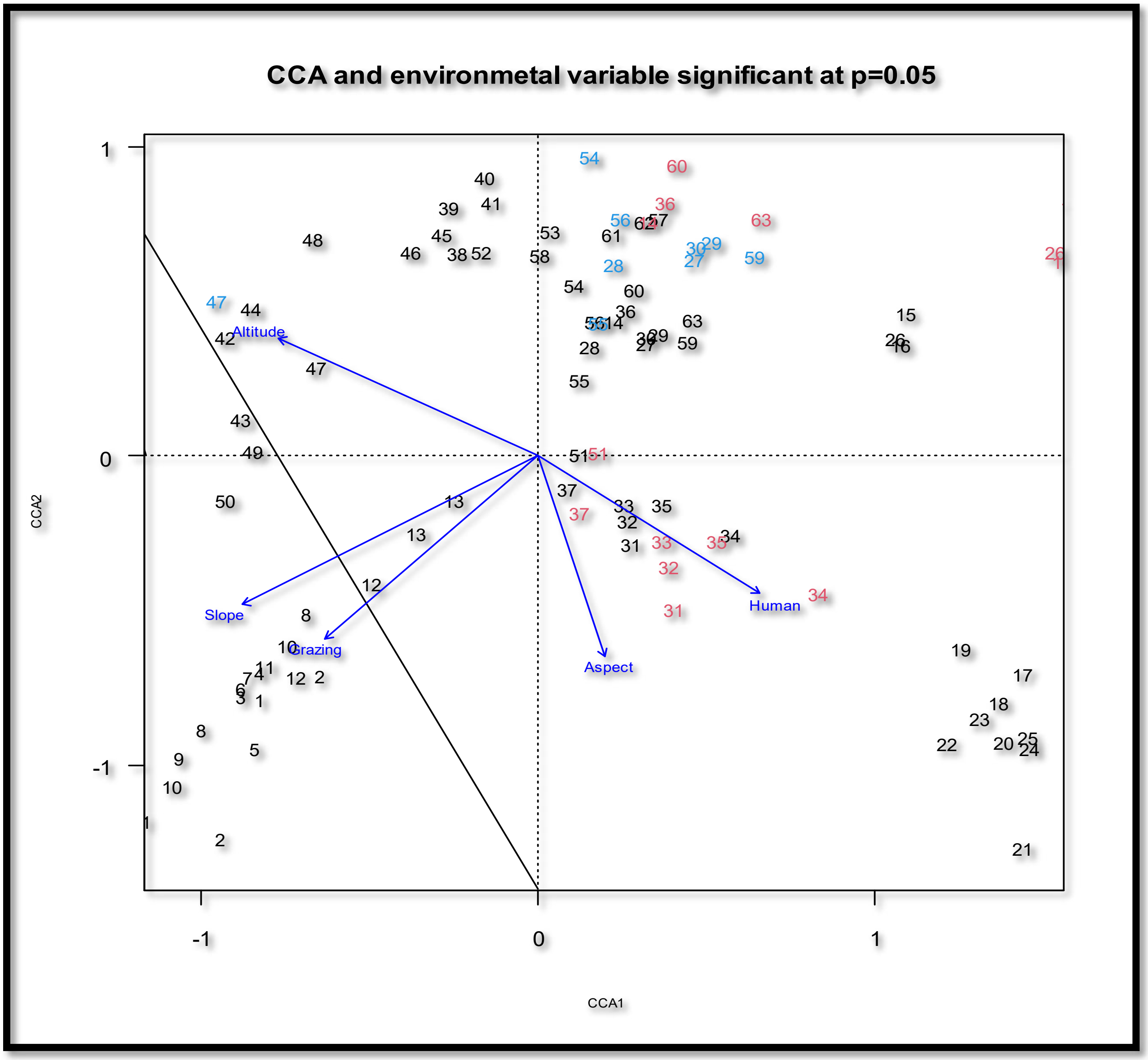

Figure 3: Canonical correspondence analysis (CCA) and environmental variables significant at P≥0.05.

Estimation of Biomass and Carbon

The distribution of biomass among above- and belowground components is essential for understanding the productivity and carbon dynamics of ecosystems. Ardibo has the largest total biomass per hectare. The Kurkur and Mersa sites exhibited comparatively elevated values of total biomass. In contrast, the intermediate range values for Geta, Bilen, Beke Meda, and Haik indicate average biomass levels. On the other hand, Mejit had the lowest total biomass per hectare, indicating very low aboveground and belowground biomass levels (Table 6).

Table 6: Estimation of aboveground (AGB) and belowground biomass at the study sites.

	Above ground biomass (ton per ha)		Below ground biomass (ton per ha)	Total Biomass (ton per ha)
Ardibo	222.8		60.2	283.0
Beke Meda	40.5		10.9	51.4
Bilen	61.1		16.5	77.6
Geta	81.2		5.5	86.6
Haik	24.3		6.6	30.9
Kurkur	103.7		28.0	131.6
Mejit	9.6		2.6	12.2
Mersa	75.0		20.2	95.2

Assessing carbon dynamics in ecosystems is important for predicting their contributions to greenhouse gas emissions and climate change mitigation. Among the studied sites, Ardibo has the highest total carbon content at 141.5 tons per hectare, which is driven by substantial aboveground and belowground carbon values. The site also contributes to sequestering relatively greater amounts of CO_2 in comparison with the remaining sites. Kurkur and Mersa also exhibited significant total carbon values in tons per hectare, reflecting their impact on carbon sequestration capacity and ecosystem productivity. Conversely, Mejit had the lowest total carbon at 6.1 tons per hectare, emphasizing the limited carbon storage potential at this site (Table 7).

Table7: Estimation of aboveground and belowground carbon at the study sites.

	Above ground carbon (ton per ha)	Below ground Carbon (ton per ha)	Total Carbon (ton per ha)	$CO_{2equ.}$
Ardibo	111.4	30.1	141.5	408.8
Beke Meda	20.2	5.5	25.7	74.2
Bilen	30.5	8.2	38.8	112.1
Geta	38.4	10.4	48.8	141.1
Haik	12.2	3.3	15.5	44.7
Kurkur	51.8	14.0	65.8	190.2
Mejit	4.8	1.3	6.1	17.7
Mersa	37.5	10.1	47.6	137.6

Discussion

Floristic Composition

Forest patches of the Wollo Islamic cultural centers have higher levels of richness. However, it was challenging to directly compare different vegetation studies. However, to offer a comprehensive overview of the species richness and variety of forests, comparisons were possible. Therefore, the floristic richness in the study sites was greater than that in some of the northern Ethiopian forests. For instance, Yegof has 123 species (Sultan Mohammed and BerhanuAbraha, 2013), the Susgen-Bosena forest has 180 species (TsegayeGobezie, 2018), and the YemrehaneKirstos Church has 39 woody species (AmanuelAyanaw and GemedoDalle, 2018). The high species richness in the studied forest patches of the Wollo Islamic Cultural Centers is linked to the availability of suitable environmental conditions, a low degree of human interference, and little disturbance.

The results from the studied forest patches showed that the dominant families Asteraceae,Poaceae and Fabaceaecontributed the most species. These families were dominant in the flora of Ethiopia and Eritrea (EnsermuKelbessa and Sebsebe Demissew, 2014). In comparison with other growth forms, herbaceous species contributed more species. The open canopy of forest patches, which allows light to reach the ground, improves the growth of herbs (Wagner et al., 2011). Six (46.2%) of the endemic taxa were found to be under the least concern threatened species category of the IUCN (Viveroet al., 2005). Therefore, Islamic Cultural Centers are home to many threatened species that need practical support for future conservation programs.

Diversity of plant species

The studied forest patches showed variation in richness, diversity, and evenness. This variation was a clear reflection of environmental factors. In comparison to the other sites, the Geta site had the most species diversity and richness. Relatively high altitudinal ranges and the collective effects of topographic, climatic, and edaphic differences, as well as the potential of species for better adaptation to different environmental conditions, have been identified (Yang et al., 2020). Similar suggestions were reported in (Alemayehu Wassie, 2007; Abiyouet al., 2011).

The studied forest patches exhibited high Shannon–Wiener diversity and high evenness values, which indicated species coexistence. However, a low evenness value was observed at the Ardibo site, indicating the dominance of a few species. Thus, the H’ values of the forest patches were within the acceptable range, indicating that the study area has a high diversity of plant species.

The forest patches with the highest βdiversity exhibited the greatest species turnover, as shown in Table 4, while the forest patches with the lowest βdiversity exhibited the least species turnover. The more prevalent co-occurring species in forest patches are connected to the narrow geographical distance and shared altitudinal range between different forest patches, which are similar environmental factors (Song et al., 2021).

Correlations between environmental variables and plant communities

The species composition of the eight sites present in the forest patches varied. These floristic changes are related to altitude, slope, aspect and human interference. Similar results were reported in Tamrat Bekele, 1993; FeyiraSenbetaet al., 2014. Due to the overlap of altitudinal ranges and the small changes in environmental gradients, there were large concentrations of comparable species throughout the sites. There is strong agreement across reports of related vegetation research that altitude is a determining factor of vegetation differences (KumelachewYeshitila and Tamrat Bekele, 2002). Additionally, plant species in mountainous areas adapt to small differences linked to altitudinal shifts that change the microclimate (Song et al., 2021).

Estimation of Biomass and Carbon

Ardibo has the highest tons of total biomass per hectare. This is due to the location at the edge of Lake Ardibo, which continuously provides water for the trees, resulting in a large diameter and height. Large tree species significantly influence plant biomass. This highlights the importance of considering both above- and belowground components when assessing carbon stocks in ecosystems (Gibbs et al., 2007). Sites such as Kurkur and Mersa also show relatively high total biomass values in tons per hectare, indicating productive ecosystems with balanced above- and belowground biomass allocation. This balance is essential for ecosystem stability and nutrient cycling (Jackson et al., 1997). The average biomass levels at the Geta, Bilen, Beke Meda, and Haik sites. These sites may offer opportunities for sustainable land management practices to maintain or enhance biomass levels while balancing other ecological and socioeconomic considerations. Conversely, Mejit had the lowest total biomass in tons per hectare, reflecting minimal biomass levels in both above- and below-ground components. Such sites may be vulnerable to environmental stressors and could benefit from restoration interventions to enhance biomass accumulation and ecosystem resilience (Wardle et al., 2004).

Regarding carbon estimation, the high carbon storage in Ardibo indicates its potential as a carbon sink, playing a vital role in offsetting CO_2 emissions and mitigating climate change impacts (Pan et al., 2011). Moreover, effective management of middle-class sites can enhance carbon storage and contribute to global efforts to reduce atmospheric CO_2 levels (IPCC, 2007). On the other hand, the sites with the lowest total carbon values in Mejit were affected by the presence of very young vegetation cover with smaller DBH values.

Conclusion

A high degree of plant diversity was found in the forest patches of sacred Islamic groves in Wollo, which was correlated with favorable environmental conditions. Asteraceae was the dominant family, followed by Fabaceae and Lamiaceae. Among the total species, 13 were endemic taxa. The Shannon–Wiener diversity index ranged from 4.3-3.2, and the evenness value ranged from 0.98-0.94, which confirmed high diversity. Among other environmental factors, altitude and slope have considerable influences on plant species distribution patterns. The distributions of AGB and BGB across different sites provide valuable insights into ecosystem functioning and carbon sequestration potential. Effective management strategies should consider both aboveground and belowground biomass components to maintain ecosystem health and sustainability in the face of global environmental changes.Thus, efforts should be made to promote sustainable forest management, reforestation, and community-based conservation initiatives to protect and restore the forest resources of sacred Islamic groves for future generations.

Reference

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Supplementary data 1: Plant species recorded in the Islamic Cultural Centers of Wollo.

Botanical Name	**Family**	**Habit**
Abutilon fruticosumGuill. &Perr.	Malvaceae	Herb
Abutilon hirtum(Lam.) Sweet	Malvaceae	Herb
Abutilon mauritianum (Jacq.) Medic.	Malvaceae	Herb
Abutilon ramosumGuill. &Perr	Malvaceae	Herb
Achyranthesaspera L.	Acanthaceae	Herb
Acokantheraschimperi (A.DC.) Schweinf.	Apocynaceae	Shrub
Agave americanaL.	Agavaceae	Herb
Airacaryophyllea L.	Poaceae	Herb
AlbiziaschimperianaOliv.	Fabaceae	Tree
Alchemillapedata A. Rich.	Rosaceae	Herb
Allophylusabyssincus(Hochst) Radlk.	Sapindaceae	Tree
Aloe camperiSchweinf.	Aloaceae	Herb
Aloe debranaChristian.	Aloaceae	Herb
Aloe weloensisSebsebe	Aloaceae	Herb
Amaranthuscaudatus L.	Amaranthaceae	Herb
AndropogonabyssinicusFresen.	Poaceae	Herb
ArgemonemexicanaL.	Papaveraceae	Herb
Argyrolobiumrupestre(E. Mey.) Walp.	Fabaceae	Herb
ArgyrolobiumramosissimumBak.	Fabaceae	Herb
Asparagus africanus Lam.	Asparagaceae	Herb
Aspleniumaethiopicum(Burm.f.) Bech.	Sinopteridaceae	Herb
BersemaabyssinicaFresen.	Melianthaceae	Tree

Bidensmacroptera (Sch. Bip. ex Chiov.) Mesfin	Asteraceae	Herb
Bidenspilosa L.	Asteraceae	Herb
Calpurnia aurea(Ait.) Bellth.	Fabaceae	Shrub
CapparistomentosaLam.	Capparaceae	Shrub
Carduusschimperi Sch. Bip. subsp. schimperi	Asteraceae	Herb
Carissa spinarum L.	Apocynaceae	Shrub
Casimiroaedulis La Llave	Rutaceae	Tree
Catha edulis (Vahl) Forssk. ex Endl.	Celastraceae	Shrub
CeltisafricanaBurm. f.	Ulmaceae	Tree
Centellaasiatica (L.) Urban	Apiaceae	Herb
Cheilalthesfarinosa (Forssk.) Kaulf	Sinopteridaceae	Herb
Chenopodium album L.	Amaranthaceae	Herb
Citrulluscolocynthis(L.) Schrad.	Solanaceae	Herb
Clematis hirsutaPerro&Guill	Ranunculaceae	Herb
Clematis simensisFresen.	Ranunculaceae	Herb
Clerodendrummyricoides (Hochst.) Vatke	Lamiaceae	Shrub
Commelinabenghalensis L.	Commelinaceae	Herb
Convolvulus kilimandschariEngl.	Convolvulaceae	climber
ConyzastrictaWilld.	Asteraceae	Herb
CordiaafricanaLam.	Boraginaceae	Tree
CordiamoniocaRoxb.	Boraginaceae	Tree
Crassocephalumsarcobasis(DC) S. Moor	Asteraceae	Herb
Crassocephalumvitellinum(Benth.) Moore	Asteraceae	Herb
CrepisfoetidaL.	Asteraceae	Herb
Crepisrueppellii Sch. Bip.	Asteraceae	Herb
Croton macrostachyusDel.	Euphorbiaceae	Tree
Cupressuslusitanica Mill.	Cupressaceae	Tree
Cynodondactylon (L.) Pers.	Poaceae	Herb
Cyphostemmaadenocaula (Steud. ex A. Rich) Desc. ex. Wild & Drummond.	Vitaceae	Climber
DaturastramoniumL.	Solanaceae	Herb
Delphinium wellbyiHemsl.	Ranunculaceae	Herb
Descopodiumpenninervum (Hochst)	Solanaceae	Shrub
Digitariaabyssinica (Hochst. ex A. Rich.) Stapf	Poaceae	Herb
DodoneaangustifoliaL f.	Sapindaceae	Shrub
Dovyalisabyssinica (A. Rich.) Warb.	Flacourtiaceae	Shrub
Dovyaliscaffra(Hook. f. &Hary.) Hook.f.	Flacourtiaceae	Shrub
Dovyalisverrucosa (Hochst.) Warb.	Flacourtiaceae	Tree

EchinopskeberichoMesfin,	Asteraceae	Shrub
Echinopslongisetus A. Rich.	Asteraceae	Shrub
EchinopsmacrochaetusFresen.	Asteraceae	Shrub
EhretiacymosaThonn.	Boraginaceae	Shrub
EkebergiacapensisSparrm.	Meliaceae	Tree
EntadaabyssinicaSteud ex A. Rich.	Fabaceae	Shrub
Eucalyptus camaldulensisDehnh.	Myrtaceae	Tree
Eucalyptus globulusLabill	Myrtaceae	Tree
EuclearacemosaMurr.subsp. schimperi (A. DC.) White	Ebenaceae	Shrub
EulophiastreptopetalaLindl.	Orchidaceae	Herb
EupborbiapolycanthaPax.	Euphorbiaceae	Herb
Euphorbia ampliphyllaPax.	Euphorbiaceae	Tree
Euphorbia candelabrumKotschy	Euphorbiaceae	Tree
Euphorbia pulcherrimaKlothsch.	Euphorbiaceae	Shrub
Euphorbia tirucalli L.	Euphorbiaceae	Tree
Ficus sur Forssk.	Moraceae	Tree
FicusvastaForssk.	Moraceae	Tree
Foeniculumvulgare Miller.	Apiaceae	Herb
Galinierasaxifraga(Hochst.) Bridson	Rubiaceae	climber
GaliumsimenseFresen.	Rubiaceae	Herb
Geranium arabicumForssk.	Geraniaceae	Herb
Gerbera piloselloides(L.) Cass.	Asteraceae	Herb
Gerbera viridifolia (DC.) Sch. Bip.	Asteraceae	Herb
Gladiolus abyssinicus(Brongn. ex Lemaire) Goldblatt& de Vos	Iridaceae	Herb
Glycine wightii(Wighti&Arn) Verdc.	Acanthaceae	Herb
Grevillea robusta R. Br.	Proteaceae	Tree
GrewiaferrugineaHochst. ex A. Rich	Tiliaceae	Shrub
GrewiaferrugineaHochst. ex A. Rich.	Tiliaceae	Shrub
GrewiasimilisK. Schum.	Tiliaceae	Shrub
GrewiatrichocarpaHochst. ex A. Rich.	Tiliaceae	Shrub
Guizotiascabra(Vis.) Chiov.	Asteraceae	Herb
HabenariatweedieaeSummerh.	Orchidaceae	Herb
Helichrysumfoetidum (L.) Moench.	Asteraceae	Herb
Helichrysumforsskahlii(J.F. Gmel.) Hilliard &Burtt	Asteraceae	Herb
Helichrysumschimperi (Sch. Bip. ex A. Rich.) Moeser	Asteraceae	Herb
Heteromorphaarborescens(Spreng.) Cham. &Schlecht.	Apiaceae	Shrub
Hyparrheniahirta (L.) Stapf	Poaceae	Herb

Hypoestesforskaolii (Vahf) R Br.	Acanthaceae	Herb
Hypoestestriflora(Forssk.) Roem. &Schult.	Acanthaceae	Herb
Ipomoea crassipes Hook. F.	Convolvulaceae	Climber
IsoglossalaxaOliv.	Acanthaceae	Herb
Jacaranda mimosifolia D. Don.	Bignoniaceae	Tree
JasminumabyssinicumHochst. ex DC.	Oleaceae	Climber
Jasminum grandiflorum L.	Oleaceae	climber
JasminumstansPax	Oleaceae	Shrub
Jatropha curcasL.	Euphorbiaceae	Tree
JuniperusproceraHochst. ex Endl.	Cupressaceae	Tree
Justiciaschimperiana(Hochst. ex Nees) T. Anders.	Acanthaceae	Shrub
KalanchoemarmorataBak.	Crassulaceae	Herb
Kalanchoepetitiana A. Rich.,	Crassulaceae	Herb
Kalaneboelanceolata (Forssk.) Pers.	Crassulaceae	Herb
LactucainermisForssk.	Asteraceae	Herb
Laggeracrispata(Vahl) Hepper& Wood	Asteraceae	Herb
Laggeratomentosa (Sch. Bip. Ex A. Rich.) Oliv. &Hiern	Asteraceae	Herb
Lantana camara L.	Verbenaceae	Shrub
Leucasabyssinica(Benth.) Briq.	Lamiaceae	Shrub
Leucasmartinicensis (Jacq.)R. Br.	Lamiaceae	Herb
Linumtrigynum L.	Linaceae	Herb
LippiaadoensisHochst. ex Walp. var. adoensis	Verbenaceae	Shrub
LoliumtemulentumL.	Poaceae	Herb
Maytenusaddat (Loes.) Sebsebe	Celastraceae	Shrub
Maytenusarbutifolia (A. Rich.) Wilezek.	Celastraceae	Shrub
Melia azedarach L.	Meliaceae	Tree
Melinisrepens (Willd.) Zizka,	Poaceae	Herb
Millettiaferruginea (Hochst.) Bak	Fabaceae	Tree
Myricasalicifolia A. Rich.	Myricaceae	Tree
MyrsineafricanaL.	Myrsinaceae	Shrub
NuxiacongestaR.Br. ex Fresen.	Stilbaceae	Shrub
OcimumforskoleiBenth.	Lamiaceae	Shrub
Ocimumgratissimum L.	Lamiaceae	Herb
OcimumlamiifoliumHochst. ex Benth.	Lamiaceae	Herb
Oleacapensis L.	Oleaceae	Tree
Oleaeuropaea subsp. cuspidata(Wall. ex G.Don) Cif.	Oleaceae	Tree
Opuntiaficus-indica(L.) Miller	Cactaceae	Herb
OsyrisquadripartitaDecn.	Santalaceae	Shrub

PanicumhochstetteriSteud.	Poaceae	Herb
Partheniumhysterophorus L.	Asteraceae	Herb
PavettaabyssinicaFresen.	Rubiaceae	Shrub
Pennisetumsphacelatum (Nees) Th. Dur. &Sehinz	Poaceae	Herb
PennisetumthunbergiiKunth	Poaceae	Herb
PeriplocalineariifoliaQuart.-Dill. & A. Rich.	Asclepiadaceae	Liana
Phagnalonphagnaloides (Hochst. ex A. Rich) Cufod.	Asteraceae	Herb
Phaulopsisimbricata(Forssk.) Sweet.	Acanthaceae	Herb
PhytolaccadodecandraL'Herit.	Phytolaccaceae	Climber
Pimpinellahirtella(Hochst) A. Rich	Apiaceae	Herb
PinusradiataD. Don	Pinaceae	Tree
PlantagolanceolataL.	Plantaginaceae	Herb
Plectranthus barbatus Andr.	Lamiaceae	Herb
PlectranthusornatusCodd.	Lamiaceae	Herb
Plumbagozeylanica L.	Plumbaginaceae	Herb
PremnaschimperiEngl.	Lamiaceae	Shrub
Psydraxschimperiana (A. Rich.) Bridson	Rubiaceae	Tree
RhamnusprinoidesL'Herit	Rhamnaceae	Shrub
Rhamnusstaddo A. Rich.	Rhamnaceae	Shrub
RhusglutinosaA. Rich subsp.glutinosa	Anacardiaceae	Tree
RhusnatalensisKrauss.	Anacardiaceae	Tree
RhusretinorrhoeaOliv.	Anacardiaceae	Tree
Ricinuscommunis L.	Euphorbiaceae	Shrub
Rosa abyssinica Lindley	Rosaceae	Shrub
Rumexabyssinicus Jacq.	Polygonaceae	Shrub
RumexnervosusVahl.	Polygonaceae	Shrub
Salvia aegypticaL.	Lamiaceae	Herb
Salvia niloticaJacq.	Lamiaceae	Herb
Salvia tillifoliaVahl.	Lamiaceae	Herb
Sansevieriaforskaoliana (Schult.f.) Hepper& Wood	Asparagaceae	Herb
Saturejaparadoxa(Vatke) Engler ex Seybold	Lamiaceae	Herb
Saturejapunctata (Benth.) Briq.	Lamiaceae	Herb
Scabiosa columbaria L.	Dipsacaceae	Herb
Scheffleraabyssinica(Hochst. ex A. Rich) Harms	Araliaceae	Tree
Schreberaalata (Hochst.) Welw	Oleaceae	Tree
SeneciolyratusForssk.	Asteraceae	Herb
Senna didymobotrya (Fresen.) Irwin &Barneby	Fabaceae	Shrub
Senna septemtrionalis (Viv.) Irwin &Barneby	Fabaceae	Shrub

SidaschimperianaHochst. ex A. Rich.	Malvaceae	Shrub
SidatenuicarpaVollesen	Malvaceae	Shrub
SideroxylonoxyacanthiumBaill.	Sapotaceae	Tree
Sizygiumguineense (Willd.) DC.subsp. guineense	Myrtaceae	Tree
SolanumincanumL .	Solanaceae	Shrub
Solanumnigrum L.	Solanaceae	Herb
SonchusoleraceusL.	Asteraceae	Herb
SoncusbipontiniAsch.	Asteraceae	Herb
Sparmanniaricinocarpa (Eckl. &Zeyh.) O. Ktze.	Tiliaceae	Herb
Sporobolusafricanus(Poir.) Robyns&Tournay	Poaceae	Herb
Stephaniaabyssinica (Dillon & A. Rich) Walp.	Menispermaceae	Climber
Strigahermonthica (Del.) Benth.	Orobanchaceae	Herb
Tagetesminuta L.	Asteraceae	Herb
Thymus schimperiRonniger	Lamiaceae	Herb
TrifoliumacauleSteud ex A. Rich.	Fabaceae	Herb
Trifoliumpratense L.	Fabaceae	Herb
TrifoliumquartinianumA. Rich.	Fabaceae	Herb
TriumfettaannuaL.	Tiliaceae	Herb
VachelliaabyssinicaHochst ex. Benth	Fabaceae	Tree
VachellialahaiSteud. &Höchst, ex Benth.	Fabaceae	Tree
VachellianegriiPic.-Serm.	Fabaceae	Tree
Vachelliapolyacantha Wild	Fabaceae	Tree
VachelliaseyalDel.	Fabaceae	Tree
VerbascumsinaiticumBenth.	Scrophulariaceae	Herb
Vernoniaadoensis Sch. Bip. ex Walp.	Asteraceae	Shrub
Vernoniaamygdalina Del.	Asteraceae	Tree
Vernonialeopoldii(Sch. Bip. ex Walp.) Vatke	Asteraceae	Shrub
Veronica abyssinicaFres.	Scrophulariaceae	Herb
Viola abyssinicaOliv.	Violaceae	Herb
Zehneriascabra(Linn. f) Sond.	Cucurbitaceae	Climber
Ziziphusspina-christi(L.) Desf.	Rhamnaceae	Tree