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THE ECOLOGICAL IMPACTS OF FOREST FRAGMENTATION IN SOUTHWEST ETHIOPIA

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Abstract

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Deforestation and fragmentation have posed a serious threat to tropical forests, leading to a loss of biodiversity and ecological disturbance. This study aimed to investigate the effects of forest fragmentation and anthropogenic disturbances on the diversity, structure, and regeneration status of woody species. Systematic sampling approach was employed to assess woody vegetation and human disturbances across four forest fragment sizes (FFSs) in 122 sample plots, each measuring 20×20 m. One-way ANOVA and Pearson correlation analyses were conducted to evaluate the impacts of fragmentation and disturbances on woody species diversity, structure, and regeneration status. The results showed that very large FFSs had higher mean species richness (S) (31.55), Shannon diversity (H´) (2.96), and evenness (E) (0.86) than large (S = 26.44, H´ = 2.68, E = 0.81), medium (S = 24.57, H´= 2.48, E = 0.78), and small FFSs (S = 22.28, H´ = 2.22, E = 0.76), with significant differences ($p < 0.001$) between very large and small FFSs. Disturbance levels varied significantly, with small FFS experiencing higher mean index (34.37). Mean stem density ranged from 613.2 to 985 individuals/ha, showing significant differences between small and very large FFSs. Mean basal area density varied from 27.68 to 60.66 m^2/ha, with significantly higher values in very large FFSs. Larger FFSs and reduced disturbances positively influence tree species regeneration. These findings underscore the negative effects of forest fragmentation and disturbances on woody species richness, diversity, structure, and regeneration in southwest Ethiopia. Urgent conservation strategies are necessary to protect these forest fragments and their biodiversity and ecosystem services.

Key words: disturbance, diversity, forest fragmentation, regeneration potential, southwest Ethiopia, woody species.

Introduction

Forests are essential for the planet's well-being, providing critical ecosystem services (Hansen et al., 2020) and supporting nearly 80% of global biodiversity (Singh et al., 2022), including about 60% of terrestrial species in tropical regions (Raj et al., 2022). However, the state forest conditions have been worsened owing to habitat loss and fragmentation (Singh et al., 2022), with tropical forest alone losing approximately 50% of their area in the last century (McFarland, 2018). Most of this deforestation occurs in developing countries (Estoque et al., 2022), with Sub-Saharan Africa contributing around 20% of tropical deforestation from 2000 to 2012 (Kim et al., 2015). This rapid loss has resulted in significant fragmentation during the previous two decades (Ma et al., 2023).

Studies have indicated that land-use/land-cover (LU/LC) changes have been the major drivers of forest decline (Lewis et al., 2015; Taubert et al., 2018; Hansen et al., 2022) primarily due to expansion of agriculture lands and increased demands linked to population growth (Hending et al., 2023). Over the past five decades, forest fragmentation has emerged as a critical threat to biodiversity (Bellard et al., 2012; Fardila et al., 2017), particularly in tropical regions, where deforestation and fragmentation have drastically affected biodiversity (Jha et al., 2005; Hending et al., 2023). This forest fragmentation significantly impacts plant species diversity, with numerous studies documenting detrimental effects (Haddad et al., 2015; Rajamurugan et al., 2021; Hending et al., 2023).

Forest fragmentation is defined as the dissection of continuous forests into smaller, isolated patches (Laurance, 2008; Sahana et al., 2015). The adverse effects of forest fragmentation on biodiversity were explained by the theory of island biogeography (MacArthur, Wilson, 1967), and this theory provides a critical framework for understanding the ecological influences of forest fragmentation. Forest fragmentation is thought to reduce plant species diversity (Soomers et al., 2013; Muluneh et al., 2021; Hending et al., 2023) and phytosociological traits such as basal area and species richness (Mohandass, Davidar, 2010; Pao, Upadhaya, 2017). Fragmentation can also foster the emergence of new species (Tripathi et al., 2010), modify the composition of regenerating plant communities (Benítez-Malvido, Martínez-Ramos, 2003), and increase the extinction risk of native plant species (Vellend et al., 2006; Rahman, 2023).

The consequences of forest fragmentation primarily affect

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habitats quality and integrity, altering physical and biological conditions (Jha et al., 2005). Such changes can disturb important ecological processes, such as genetic exchange (Ibáñez et al., 2014) and nutrient cycling (Fahrig, 2003). Additionally, fragmentation enhances access to interior forests, exacerbating activities such as hunting, logging, and agricultural land use (Broadbent et al., 2008; Slattery, Fenner, 2021), which can interfere with plant reproduction, pollination, and dispersal (Benítez-Malvido, 1998). Studies (e.g., Echeverría et al., 2007; Muluneh et al., 2021) have shown that forest fragmentation, combined with human disturbances, significantly reduces woody species diversity and structural integrity.

The significance of fragments on plant diversity and structural characteristics is a topic of extensive debate, with one view asserting that large fragments can support more species (Majumdar, Datta, 2016; Muluneh et al., 2021). Conversely, certain studies indicated that species diversity does not always correlate with the size of fragments (Rajamurugan et al., 2017). Research studies by Arroyo-Rodríguez et al. (2009) and Pao and Upadhaya (2017) have found that smaller fragments supported higher levels of biodiversity than larger forest patches. Hernandez-Ruedas et al. (2014) also observed that there was no significant difference in trees species between small and large forest patches. Fahrig (2020) found that a network of small fragments can promote greater plant species diversity than a single large fragment, highlighting the importance of multiple small fragments in conservation efforts. Godefroid and Koedam (2003) also noted that small fragments can achieve species diversity comparable to that of larger habitats, emphasizing their critical role in biodiversity conservation initiatives.

The impacts of forest fragmentation and associated human disturbances on biodiversity can vary significantly across locations (Haddad et al., 2015; Malcolm et al., 2017; Razafindratsima et al., 2018). These impacts differ notably among various forest types and disturbance gradients, affecting floral and structural diversity in distinct ways (Hending et al., 2023). Additionally, these effects are heavily influenced by specific geographical contexts, with some studies reporting positive effects while others highlighting negative outcomes for floral and structural diversity (Hending et al., 2023). The magnitude and nature of these impacts also depend on site-specific conditions, ecosystem types, and the characteristics of plant species (Echeverría et al., 2007; Haddad et al., 2015). This stresses the complexity of biodiversity response to forest fragmentation and the need to identify unique local characteristics to mitigate its impact.

The forest ecosystem in southwestern Ethiopia is the birthplace of *Coffea arabica* L. (Senbeta, Denich, 2006; Tadesse et al., 2014) and is situated within the Eastern Afromontane Biodiversity Hotspot (Schmitt, 2006). This area contains one of the remnant forest blocks (Wood et al., 2019) and represents a major vegetation type in the country (Friis, 1992). It also serves as a source of various forest-related goods and services essential at both national and local levels (Tadesse et al., 2014; Masha et al., 2024). Since the 1970s, however, southwest Ethiopia has been experiencing substantial deforestation problems driven by excessive logging, human settlement, and commercial development (Wiersum, 2010). Furthermore, Mengist et al. (2022) and Mulatu et al. (2024) highlighted the significant forest fragmentation over the past three decades due to human activities. Rapid population growth, complex policies, and economic pressures continue to pose threats to forest biodiversity, resulting further forest fragmentation (Tadesse et al., 2014; Fashing et al., 2022; Senbeta et al., 2014; Lemenih, 2024; Mulatu et al., 2024).

However, despite the significant deforestation and fragmentation, there is limited understanding of the local impact of forest fragmentation and disturbance on vegetation diversity in the region. Existing research has mainly focused on analyzing vegetation structure and community composition (Senbeta et al., 2014; Kefalew et al., 2022; Sewale, Mammo, 2020), assessing the impact of forest management regimes on plant diversity (Geeraert et al., 2019; Wood et al., 2019), and comparing vegetation diversity across various land-use/land-cover scenarios related to forest cover changes (Tadesse et al., 2014; Kebebew, Ozanne, 2022) as well as forest cover change analysis (Gubila et al., 2024; Mulatu et al., 2025).

To safeguard the Afromontane forest ecosystem in southwestern Ethiopia, it is crucial to understand the effects of ongoing forest fragmentation on plant diversity, highlighting the urgent need for research in these biodiversity hotspots (Asefa et al., 2020). Currently, there is a significant lack of scientific evidence regarding how forest fragmentation affects woody species diversity, structure, and regeneration in the region. Grasping the localized effects of forest fragmentation is vital for the effective management and restoration of priority conservation areas, which are essential for preserving threatened floral and faunal diversity found in the unique niches of these forests. This study aims to explore the impact of forest fragmentation on the composition, diversity, structural attributes, and natural regeneration of woody plants in southwestern Ethiopia.

Material and methods

Description of the study area

This study was conducted in the Shey-Bench district of the Bench Sheko Zone located in Southwestern Ethiopian People's Regional States. The study area is defined by latitudes from 6°44´22″N to 7°4´45″N and longitudes from 35°36´14″E to 35°53´E (Fig. 1). The forest in the study area belongs to the vegetation type of moist evergreen Afromontane forests (Friis et al., 2010). Forests in study area are highly fragmented and isolated, resulting in smaller and more heterogeneous patches due to agriculture expansion and settlement (Mulatu et al., 2024).

The altitude of the study area ranges from 1,327 to 2,653 m above sea level. The reference evapotranspiration is 1259 (±12) mm per year, and the average annual precipitation is 1780 (±270) mm per year (FAO, 2006). The mean air temperature ranges from 13 to 27 °C (Tadesse et al., 2006). Leptosols, Fluvisols, and Nitisols are the dominant soil types in the area (Dewitte et al., 2013).

Selection of forest fragments

The study area consists of several forest patches (Mulatu et al., 2024), with a total of 12 forest fragments selected based on similar environmental conditions such as elevation, topography, and soil factors (Ma et al., 2015; Muluneh et al., 2021). Selection methods included Google Earth, reconnaissance surveys, and forest cover data from the district's Forest and Environmental Protection Office. The fragments were categorized into four

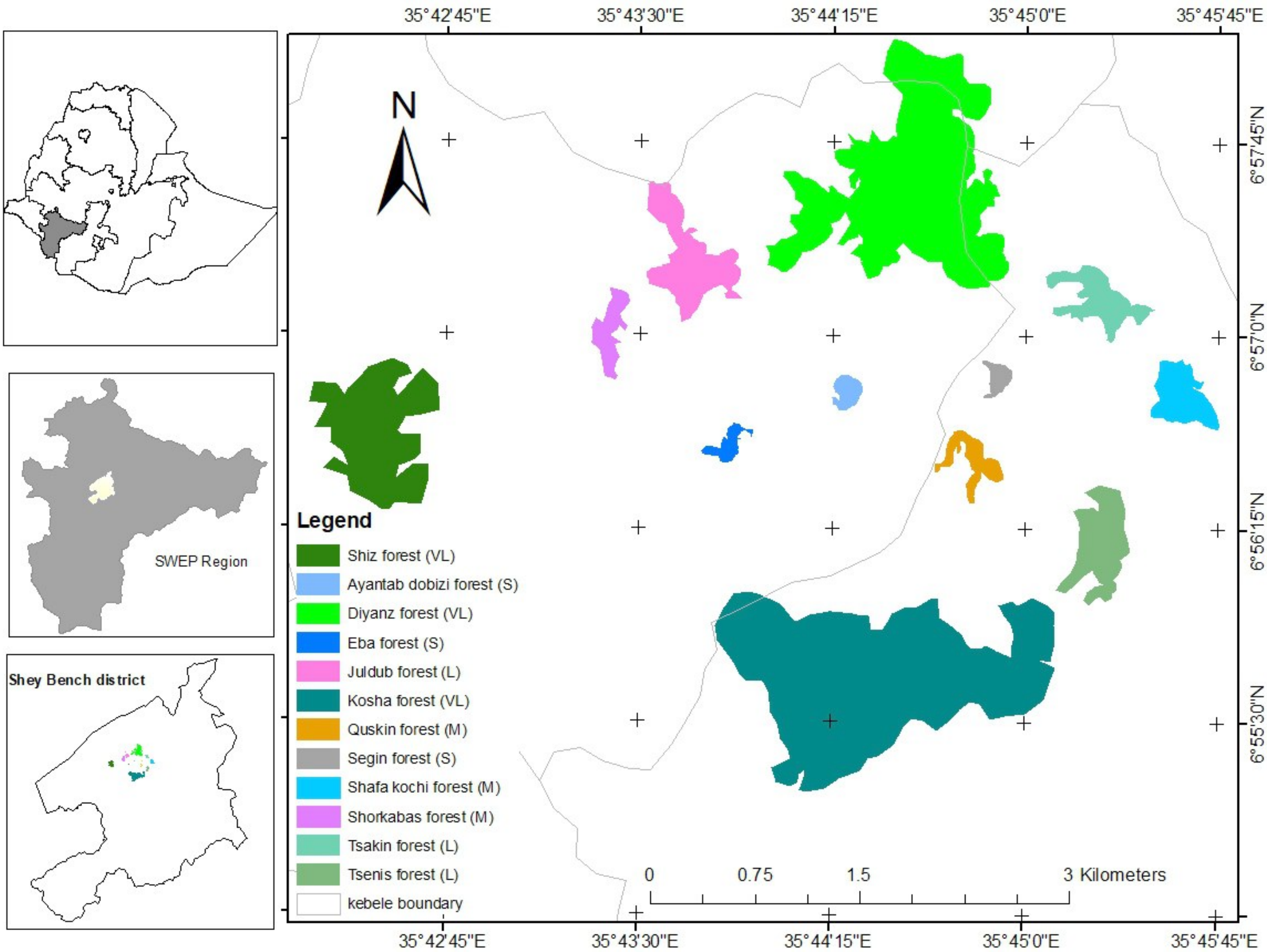

Fig. 1. Map of the study area, indicating forest fragment sizes: VL – very large, L – large, M – medium, and S – small.

forest fragment sizes (FFSs): small (<5.0 ha), medium (5.0–15 ha), large (16.0–60 ha), and very large (>60 ha), each with three replications. These size classifications are informed by ecological principles regarding species needs and conservation goals, aiding in the analysis of fragmentation effects on woody diversity and guiding conservation strategies. Similar methodologies have been employed in other studies (Mohandass, Davidar, 2010; Majumdar, Datta, 2016; Pao, Upadhaya, 2017; Muluneh et al., 2021; Assefa, Gobezie, 2022). The distances between the forest fragments ranged from 250 m to 2.5 km. The size of each fragment was also measured using Google Earth and confirmed at the office of Shey Bench Forest and Environmental Protection. The studied forest fragments cover a total area of 529.87 ha.

The number of study plots investigated within each fragment varied depending on the size of the forest fragment (Senbeta et al., 2014; Wekesa et al., 2019; Muluneh et al., 2021). A total of 18 plots were established in small FFSs, 23 in medium FFSs, 34 in large FFSs, and 47 in very large FFSs, with each plot measuring 20×20 m. This resulted in a total sampling area of 4.88 ha, representing 0.92% of the overall study area. This sampling effort exceeds the minimum recommended intensity of 0.01% for investigating the impacts of fragment size, as outlined by Sukumar et al. (1992). The sampling intensities for each fragment size category were as follows: 5.97% for small fragments, 2.94% for medium fragments, 1.86% for large fragments, and 0.46% for very large fragments.

Vegetation sampling procedure

Vegetation surveys in each forest fragment were carried out using systematic sampling methods (Kent, 2012; Eyasu et al., 2020). To ensure a representative sample across all FFSs, transect lines were established along an altitude gradient (Berhanu et al., 2017; Muluneh et al., 2021). The first-line transect was randomly positioned at least 20 m from the forest edge to avoid edge effect. The distance between parallel transects varied between 100 and 300 m depending on the size of the forest fragment. This transect approach is widely recognized as an effective method for vegetation sampling and monitoring, often regarded as the most efficient design for surveying multiple species (Kent, 2012; Muluneh et al., 2021).

A nested plot design was employed to assess woody plant species (trees, shrubs, and lianas), following the guidelines suggested by previous studies (Kent, 2012). Within each plot, all shrubs and trees with a diameter at breast height (DBH) of ≥2.5 cm and a height of ≥1.5 m were counted. In addition, five smaller subplots, each measuring 5×5 m (25 m²), were established at the four corners and the center of each 20×20 m plot to quantify seedlings and saplings.

In each 20×20 m plot, the DBH for live stems measured at 1.3 m above ground level for all woody species with a height of ≥1.5 m and a DBH of ≥2.5 cm. The number of logged stems was counted, and their stump height diameter (DSH) measured 30 cm above ground level (Muluneh et al., 2021). In this study, "stumps" refer to the small sections of the stems that remain after trees have been felled, with a minimum diameter of 2.5 cm. DSH measurements were conducted to evaluate the extent of disturbances mainly caused by selective logging (Aguilar-Santelises, Castillo, 2013; Muluneh et al., 2021; Kassahun et al., 2024).

Plants with a DBH <2.5 cm and a height ≤0.6 m were classified as seedlings, while those with a DBH <2.5 cm and a height between 0.61 and 1.5 m were classified as saplings, following the criteria established by Kumal and Shibru (2015). Tree diameter was measured using calipers and/or diameter tapes, while the height of each tree was measured with a Suunto clinometer.

Species identification was carried out in the field, and specimens that could not be identified on-site were pressed and taken to Mizan-Tepi University for identification using published volumes of the Flora of Ethiopia and Eritrea (Hedberg, Edwards, 1989; Edwards et al., 1995, 2000; Hedberg et al., 2003, 2006).

Data analysis

Diversity data were analyzed for Shannon-Wiener (H´) and Pielou's evenness index (J´) following Kent (2012). The Shannon index was calculated as follows:

$$H' = -\sum (P_i)\,(\ln P_i), \tag{1}$$

where *Pi* is the proportion of individuals or the abundance of the i^{th} species and ln = log base$_n$. Pielou's evenness index (J´) was calculated as follows:

$$J' = \frac{H'}{H'_{max}} = \frac{H'}{\ln S}, \tag{2}$$

where S is the number of species (species richness) and H´ is the Shannon-Wiener diversity indices.

To compare the floristic similarity between the forest fragments, we employed the Jaccard coefficient of similarity (S_J) calculated as follows:

$$S_J = \frac{\mathrm{a}}{\mathrm{a}+\mathrm{b}+\mathrm{c}}, \tag{3}$$

In this formula, a is the number of species common to both forest fragments, b is the number of species found only in forest fragment 1, and c is the number of species found only in forest fragment 2.

The structure of woody species was examined by analyzing stand density and basal area density. Basal area is the cross-sectional area of tree stems at breast height, indicating species dominance in a forest for trees with a diameter at breast height (DBH) of 2.5 cm or greater. Woody species density is a vital parameter in vegetation analysis, calculated by summing stems with a diameter at breast height of 2.5 cm or greater and converting this total to a per-hectare basis.

The regeneration status of forest woody species was categorized into five levels based on tree density: Good: seedlings > saplings > matures; Fair: seedlings > or ≤ saplings ≥ matures; Poor: saplings, but no seedlings (though saplings < or ≥ matures); None: only adults present; and New: matures absent, but saplings and/or seedlings present (Maua et al., 2020). The percentage regeneration potential of tree species in each FFS was calculated by dividing the number of species in each regeneration category by the total number of species across all categories and multiplying by one hundred, as detailed by Pradhan et al. (2018).

Human disturbances, particularly selective logging, were the primary drivers of fragmentation in forests. Disturbance levels were assessed in each FSC using the basal area of stumps (Aguilar-Santelises, Castillo, 2013; Borah et al., 2014). The disturbance index was calculated with the following formula:

$$\mathrm{DI}(\%) = \frac{BA_{CST}}{\mathrm{BA_T}} \times 100, \tag{4}$$

where DI is the disturbance index, BA_{CST} is the total basal area of cut stumps, and BA_T is the total basal area of both cut stumps and standing trees.

Pearson correlation analysis was performed to examine the effect of fragment size and disturbances on density, regeneration status, basal area, and various diversity indices. One-way ANOVA, followed by LSD post hoc tests (α= 0.05), was used to examine whether fragments of different size classes were significantly different in Shannon diversity and structural attributes, such as basal area density and stem density, density of seedlings, and saplings within fragments. The software SPSS statistical package (Version 23) was used for statistical analysis.

Results and discussion

Composition and diversity of woody species

The species accumulation curve for forest fragments levels off at different sampling plot sizes. For instance, in very large forests, it stabilized at a sampling intensity of 1.08 ha, while for large forests, it was 0.56 ha. In medium and small fragments, the curve flattened at 0.48 ha (Fig. 2). This indicates that the total number of sample plots used in the study was adequate.

A total of 83 woody species from 40 families were recorded in the studied FFSs. Specifically, there were 76 species in 36 families in very large FFSs, 65 species in 32 families in large FFSs, 57 species in 32 families in medium FFSs, and 52 species in 29 families in small FFSs. The proportion of woody species linked to each FFS ranged from 30.11% in very large FFSs to 20.88% in small FFSs, highlighting the differing responses of woody species to forest fragmentation and associated disturbances. These findings demonstrated that larger forest fragments harbor a greater number of woody species compared to smaller forest patches. The study found that in very large FFS, the dominant plant families were Euphorbiaceae (eight species) and Rubiaceae (six species), followed by Malvaceae and Fabaceae (five species each). Large FFS had Euphorbiaceae (seven species) and Rubiaceae (six species) as well, with Asteraceae and Fabaceae contributing five species each. In medium FFS, Euphorbiaceae and Rubiaceae each

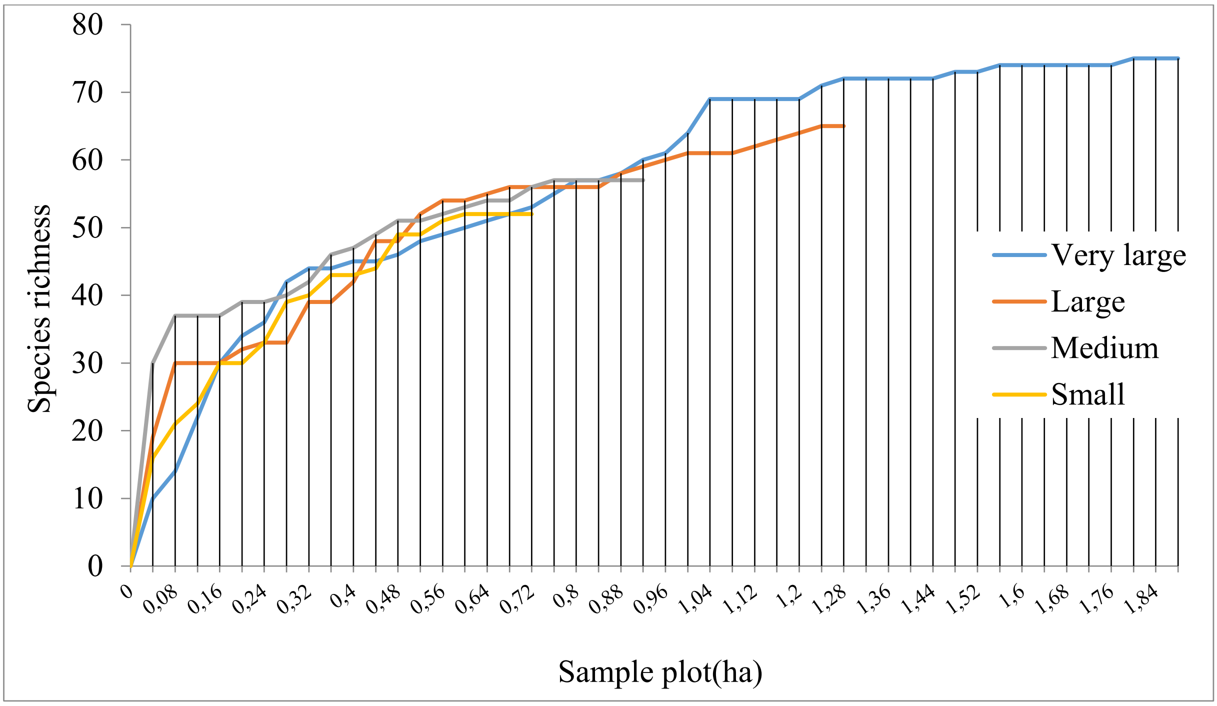

Fig. 2. Species accumulation curve of studied forest fragments.

Table 1. Woody species diversity in the study FFSs in southwest Ethiopia.

FSC	Mean±stand. Dev.			
	Richness	Shannon Diversity	Evenness	Disturbance index (DI)
Very large	31.55^{a} ±4.48	2.96^{a} ±0.20	0.86^{a} ±0.06	9.27^{a} ±7.31
Large	26.44^{b} ±5.09	2.68^{b} ±0.47	0.81^{b} ±0.09	11.16^{a} ±10.86
Medium	24.57^{bc} ±5.22	2.48^{b} ±0.51	0.78^{b} ±0.09	20.35^{b} ±9.59
Small	22.28^{cd} ±4.97	2.22^{c} ±0.43	0.76^{c} ±0.07	34.37^{c} ±16.45
Total	27.44±6.37	2.68±0.47	0.82±0.09	16.03±13.86

Note: Means with the same superscript letter in a column are not significantly different from each other at p <0.05.

Table 2. Pearson's correlation between fragment size, phytosociological attributes and disturbance in the study FFSs.

	A	**S**	**H´**	**E**	**DI**	**BA**	**NCS**	**StD**	**SaD**	**SeD**
A	1	0.48	0.73^{**}	0.63^{*}	-0.83^{**}	0.50	-0.53	0.46	0.15	0.31
S		1	0.78^{**}	0.24	-0.56	0.46	-0.44	0.18	0.21	0.72^{**}
H´			1	0.58^{*}	-0.53	0.58^{*}	-0.41	0.10	0.34	0.72^{**}
E				1	-0.39	0.22	0.07	0.01	0.59^{*}	0.42
DI					1	-0.54	0.78^{**}	-0.74^{**}	-0.22	-0.31
BA						1	-0.59^{*}	0.59^{*}	0.26	0.50
NCS							1	-0.75^{**}	-0.06	-0.27
StD								1	0.16	0.17
SaD									1	0.62^{*}
SdD										1

Notes: *P < 0.05 and **P < 0.001; A – fragment size; S – richness; H´ – Shannon diversity; E – evenness; DI – disturbance index; BA – basal area; StD – stem density (ha^{-1}); NCS – number of cut stumps; SaD – Sapling density(ha^{-1}); SeD – Seedling density (ha^{-1}).

Table 3. Jaccard coefficient of similarity of woody species among forest fragments in the southwestern Ethiopia.

	VL_1	**VL_2**	**VL_3**	**L_1**	**L_2**	**L_3**	**M_1**	**M_2**	**M_3**	**S_1**	**S_2**	**S_3**
VL_1	1	0.69	0.61	0.63	0.64	0.47	0.62	0.36	0.49	0.41	0.47	0.30
VL_2		1	0.64	0.64	0.65	0.49	0.50	0.42	0.55	0.43	0.64	0.36
VL_3			1	0.58	0.67	0.55	0.63	0.48	0.56	0.60	0.53	0.37
L_1				1	0.40	0.77	0.547	0.66	0.47	0.59	0.53	0.58
L_2					1	0.59	0.56	0.62	0.61	0.58	0.45	0.41
L_3						1	0.61	0.57	0.58	0.43	0.59	0.55
M_1							1	0.44	0.56	0.52	0.57	0.38
M_2								1	0.56	0.52	0.45	0.52
M_3									1	0.62	0.63	0.43
S_1										1	0.57	0.51
S_2											1	0.48
S_3												1

Notes: VL – very large; L – large; M – medium; S – small-sized forest fragment, with the number in subscript indicating the level of replication.

represented five species, while small FFS saw Euphorbiaceae (six species), Asteraceae (five species), and Fabaceae (five species) leading. Overall, Euphorbiaceae and Rubiaceae were consistently dominant across all sizes, with larger forests supporting greater diversity and smaller forests having fewer families and species.

The analysis indicated that very large FFSs exhibit significantly higher mean species richness (31.55), Shannon diversity index (2.96), and Pielou's evenness index (0.86) than other FFSs. These metrics indicate that larger forests can sustain a more diverse array of species and maintain a balanced representation within the ecosystem. Additionally, large forest fragments exhibited an average species richness of 26.44, the Shannon diversity index of 2.68, and Pielou's evenness index of 0.81 (Table 1). Although these values are relatively high, they indicate a decrease in both richness and species diversity when compared to very large fragments. Medium-sized fragments displayed even greater declines, reflecting a mean species richness of 24.57, the Shannon index of 2.48, and a Pielou's evenness score of 0.78. Small forest fragments recorded the lowest metrics, with a species richness of 22.28 and the Shannon diversity index of 2.22.

However, no significant mean differences were observed between large- and medium-sized FFSs regarding the analyzed indices. The findings provide important insights into the connection between forest size and biodiversity metrics. A clear trend was observed, indicating that as forest size diminishes, the corresponding biodiversity parameters also decline. The correlation coefficient (Ratner, 2009) showed that there exists a strongly significant relationship between species diversity and fragment size ($r = 0.73$, $p < 0.01$) (Table 2). These results underscore the crucial importance of larger forest areas in fostering plant diversity. The findings indicate that the forest fragments in the study area are subjected to varying levels of disturbance due to illegal logging, with the mean disturbance index (DI) for small FFSs being significantly higher than that of the other FFSs (Table 1).

The differences in diversity among the FFSs may be influenced by factors such as land-use history, human disturbances, and proximity to settlements (Echeverria et al., 2007; Pao, Upadhaya, 2017). Research has shown that smaller fragments tend to exhibit lower species richness and diversity compared to larger fragments (Muluneh et al., 2021; Aguirre-Jaimes et al., 2021; Asefa, Gobezie, 2022; Hending et al., 2023). Hending et al. (2023) found that habitat degradation resulting from forest fragmentation and edge effects exacerbates the decline in species diversity as the size of the forest decreases.

Our findings revealed a strong, significant negative correlation between the disturbance index and the species diversity index (H′) ($r = -0.83$, $p < 0.01$). According to Muluneh et al. (2021), forest fragments were categorized based on disturbance levels into three groups: low (7–13% DI), medium (17–23% DI), and high (29–33% DI). In this framework, smaller forest fragments were identified as highly disturbed, whereas very large fragments were classified as having low disturbance. Furthermore, studies by Bentsi-Enchill et al. (2022) and Kassahun et al. (2024) reported a decline in species richness and diversity in heavily disturbed forest regions.

The similarity in woody species composition among FFSs varies, ranging from 30% between VL1 and S3 to 77% between L2 and L3 (Table 3). The average similarities for very large, large, medium, and small FFSs are 65.41, 59.79, 52 and 52.11%, respectively, indicating a trend where similarity diminishes with a decreasing fragment size. Very large FFSs exhibited average similarities of 58.76% with large FFSs, 51.1% with medium FFSs, and 45.63% with small FFSs. Notably, the similarity between large and medium FFSs was 58%, while it decreased to 53.5% between large and small FFSs, highlighting a diminishing pattern.

Despite evidence showing that geographical proximity and environmental similarities positively influence species similarity (Durigan et al., 2008; Pao, Upadhaya, 2017), our findings reveal reduced similarity between large and small forest fragments. This decrease is likely due to edge effects and increased human disturbances associated with smaller fragments. Hending et al. (2023) revealed that forest fragmentation and edge effects lead to fewer tree species, especially in smaller fragments. Ashworth and Martí (2011) noted that fragmentation adversely affects germination and plant population viability, causing differences in species composition between fragment sizes. Pao and Upadhaya (2017) also discussed the combined negative influences of fragmentation and disturbance. As habitat quality declines, smaller fragments lose shade-loving species and become dominated by opportunistic species, further decreasing similarity to larger

Table 4. Structural parameter of woody species in the study forest fragments.

FFSs	Structural parameters (Mean±Stand. Dev.)			
	Basal area (m^2/ha)	Stem density ha^{-1}	Sapling ha^{-1}	Seedling ha^{-1}
Very Large	60.66^{a}±52.03	985.16^{a}±451.83	4,564.67^{a}±935.27	8,977.03^{a}±682.81
Large	43.53^{a}±41.63	748.94^{bc}±275.59	3,409.67^{a}±664.47	7,710.76^{a}±409.63
Medium	44.17^{a}±29.42	789.13^{c}±334.04	4,024.0^{a}±857.62	6,609.66^{a}±599.92
Small	27.68^{b}±14.04	613.16^{cd}±200.93	2,819.0^{a}±669.545	5,460.42^{a}±785.56
Total	45.69±44.27	797.73±352.24	3,704.33±466.60	7,189.46±343.10

Note: Means with different superscript letters in a column are significantly different at $p < 0.05$.

fragments. Previous studies reported similarity indices from 52 to 77% (Pao, Upadhaya, 2017) and from 40 to 77.2% (Muluneh et al., 2021) across differently sized forest fragments.

Density and basal area

The mean stem density varied by FFS with low density (613.2 individuals/ha) in small FFSs to higher density (985 individuals/ha) in very large FFSs (Table 4). The mean stem density of very large FFSs was significantly higher than that of other FFSs. However, no significant differences were found among large, medium, and small FFSs. The dominant species in terms of density across all FFSs were *Macaranga capensis* and *Syzygium guineense*. The next most predominant species in both very large and large forest fragments were *Psychotria nervosa* and *Ilex mitis*, while Ilex mitis and *Cyathea manniana* ranked as the next most dominant species in medium and small fragments, respectively. The dominance of species such as *Macaranga capensis* and *Syzygium guineense* across different forest sizes may be attributed to their adaptability to varying environmental conditions and disturbances, allowing them to thrive in fragmented habitats.

The mean basal area density exhibited an increasing trend with the size of the forest fragments, ranging from 27.68 m^2/ha in small FFSs to 60.66 m^2/ha in very large FFSs, with an overall mean of 45.69 m^2/ha. The difference was significantly greater between very large FFSs and small FFSs. Correlation results also support this finding, showing a moderate positive correlation between basal area and forest fragment size ($r = 0.47$, $p = 0.12$). This trend can be attributed to the higher number of individual trees in the larger forest fragments, which contributed to the increased basal area. The findings of Muluneh et al. (2021) and Majumdar and Datta (2016) align with this study, indicating that larger FFSs support a higher stem density per hectare due to their ability to accommodate more individuals.

Furthermore, a moderately significant negative correlation was observed between basal area density and the number of cut stumps ($r = -0.59$, $p < 0.05$), along with a moderately negative relationship with the disturbance index ($r = -0.54$, $p = 0.07$). These findings indicate that the increase in disturbances within smaller FFSs, caused by the excessive harvesting of trees with larger diameters, has led to a decline in basal area density. This observation is consistent with the reports by Atkinson and Marin-Spotta (2015) and Pao and Upadhaya (2017), who noted that forest fragments experiencing the highest levels of disturbance often have lower basal areas. Furthermore, Pao and Upadhaya (2017) and Kassahun et al. (2024) corroborated this trend, highlighting that increased logging intensity and disturbances lead to decreases in basal area. The reduction in basal area within smaller fragments exhibiting a higher disturbance index suggests alterations in stand structure, indicative of an earlier successional stage within the small FFSs (Echeverria et al., 2007).

Small forest fragments usually receive little protection from government and community initiatives and apparently exposed to severe disturbances. The impact of disturbances also varies among species due to differences in local community preferences for construction, timber, and fuelwood. The distribution of tree species in terms of basal area density was shaped by local community needs, driven by the high demand for timber and construction materials. Research by Gebrehiwot and Hundera (2014) highlighted how the demand for specific species with larger diameters in the moist evergreen Afromontane forest influenced this distribution. Notably, as forest areas shrink, the growth and survival of these species are further threatened by increased edge effects, habitat fragmentation, and competitive dynamics.

Regeneration status

The regeneration profile of a woody species is reflected by the balance of seedlings, saplings, and matures. Effective recruitment and a balanced presence of these stages indicate successful and healthy forest ecosystem regeneration (Temesgen, Warkineh, 2020).

The mean sapling density of the study forest fragments ranges from 2,819 to 4,564.67 per ha, while the mean seedling density varies from 5,460.42 to 8,977 per ha. Sapling density is highest in large forest fragments, while seedling density decreases with the fragment size (Table 4). The study also showed a weak-to-moderate positive relationship between sapling density and fragment size and a weak-to-moderate negative relationship between seedling density and disturbance index (Table 2).

High sapling and seedling densities in very large forest fragments are due to better growth conditions and low disturbance, while smaller FFSs suffer from issues like uncontrolled grazing. This finding is in line with the finding reported by Assefa and Gobezie (2022), while Muluneh et al. (2021) reported the highest densities of seedlings and saplings density in small FFSs. But both studies found non-significant differences in sapling and seedling densities across FFSs. The regeneration condition of tree species in all FFSs is good, with seedling density

Table 5. Regeneration status of tree species in the studied FFSs in southwest Ethiopia.

Regeneration status	Regeneration potential of FFSs (%)			
	Very large	Large	Medium	Small
Good regeneration	58.18	30.77	48.84	28.21
Fair regeneration	12.73	30.77	18.6	17.95
Poor regeneration	1.82	5.77	2.33	0
No regeneration	0	3.85	2.33	2.56
Newly recruit	27.27	28.85	27.91	51.28
Total	100	100	100	100

greater than saplings and adults (Table 4). Most species are well-recruited or have new regeneration (Table 5). The highest percentage of species with good regeneration (58.18%) was in very large FFSs, followed by medium-sized FFSs (48.84%). Small FFSs had the lowest percentage (28.21%), while large FFSs showed intermediate potential (30.77%).

In small FFSs, newly recruited tree species as seedlings and saplings accounted for 51.28%, while only 28.85% in large FFSs, 27.91% in medium FFSs, and 27.27% in very large FFSs. This high recruitment in small FFSs may indicate viable soil seed banks, suggesting a potential shift in species composition (Pradhan et al., 2018).

The differences in regeneration status among FSC classes may be attributed to variations in environmental conditions and levels of human disturbance within each FSC. Human disturbances play a significant role in determining the success of regeneration (Cotler, Ortega-Larrocea, 2006). Similarly, Agramont et al. (2012) found that logging and grazing negatively impact the recruitment of key tree species. Gebeyehu et al. (2019) and Kassahun et al. (2024) also reported the adverse effects of overgrazing on seedlings and saplings.

Larger forest fragments offer benefits over smaller areas, including diverse habitats, more resources (Schoener, 2010; Pradhan et al., 2018), reduced susceptibility to human disturbances (Cayuela et al., 2006; Tripathi, Reynald, 2010), and greater genetic diversity, which enhances resilience and adaptability to disturbances. This contributes to better forest conditions and higher seedling and sapling growth compared to small FFSs. Conversely, the increased vulnerability of small FFSs to disturbances and higher edge effects may lead to greater exposure to invasion by new species, particularly invasive ones, which could hinder regeneration. Furthermore, increased overexploitation could result in a reduction or absence of adult trees in small FFSs. As noted by Pradhan et al. (2018), high levels of new recruitment in small FFSs indicate that these forests are secondary and undergoing regeneration.

Species such as *Trilepisium madagascariense*, *Polyscias fulva*, and *Sapium ellipticum* show no regeneration in small, medium, and large FFSs, respectively. In very large FFSs, *Hagenia abyssinica* has poor regeneration, while *Vepris dainellii*, *Ekebergia capensis*, and *Euphorbia candelabrum* show poor regeneration in large FFSs. These species may face future risks within their respective FFSs (Malik, Bhat, 2016; Pradhan et al., 2018). The lack of regeneration may be due to low or uncertain seed supply, insufficient favorable micro-sites, and factors hindering early seedling growth and survival in different FFSs (Clark et al., 1999).

Conclusion

This study has provided crucial insights into the conservation potential of forest fragments in southwest Ethiopia, a region critical in maintaining global biodiversity. Our findings suggest that both fragment size and disturbance level can significantly impact the species richness, diversity, evenness, and structural attributes of forest fragments. Specifically, the study found that larger fragment sizes contribute positively to species diversity, while disturbances negatively affect forest structure and species richness. Notably, very large forest fragments exhibited higher regeneration rates, reinforcing their importance in fostering healthy regeneration. Conversely, small forest fragments displayed significant recruitment of new woody species, indicating the establishment of secondary succession communities following forest fragmentation. Moreover, our results indicate that larger forests harbor more rare species, highlighting their crucial role in conserving biodiversity. The detrimental effects of increased fragmentation and disturbance on species richness, diversity, and forest structure further underscore the urgency of implementing a comprehensive conservation strategy. To safeguard these vital ecosystems, we recommend an expedited conservation plan to protect the remaining forests in southwest Ethiopia, ensuring their continued contribution to global biodiversity and ecosystem services while mitigating the impacts of climate change.

References

Agramont, A.R.E., Maass, S.F., Bernal, G.N., Hernández, J.I.V. & Fredericksen T.S. (2012). Effect of human disturbance on the structure and regeneration of forests in the Nevado de Toluca National Park, Mexico. *J. For. Res.*, 23, 39–44. DOI: 10.1007/s11676-012-0226-8.

Aguilar-Santelises, R. & del Castillo R.F. (2013). Factors affecting woody plant species diversity of fragmented seasonally dry oak forests in the Mixteca Alta, Oaxaca, Mexico. *Revista Mexicana de Biodiversidad*, 84(2), 575–590. DOI: 10.7550/rmb.30458.

Aguirre-Jaimes, A., López-Acosta, J.C. & Dirzo R. (2021). Tropical rainforest fragmentation affects plant species richness, composition and abundance depending on plant-size class and life history. *Botanical Sciences*, 99(1), 92–103. DOI: 10.17129/botsci.2679.

Arroyo-Rodríguez, V., Pineda, E., Escobar, F. & Benítez-Malvido J. (2009). Value of small patches in the conservation of plant-species diversity in highly fragmented rainforest. *Conserv. Biol.*, 23, 729–739. DOI: 10.1111/j.1523-1739.2008.01120.x.

Asefa, M., Cao, M., He, Y., Mekonnen, E., Song, X. & Yang J. (2020). Ethiopian vegetation types, climate and topography. *Plant Diversity*, 42, 302–311. DOI: 10.1016/j.pld.2020.04.004.

Ashworth, L. & Martí M.L. (2011). Forest fragmentation and seed germination of native species from the Chaco Serrano Forest. *Biotropica*, 43(4), 496-503. DOI: 10.1111/j.1744-7429.2010.00721.x.

Assefa, F. & Gobezie T. (2022). Effects of Forest Fragmentation on Plant Diversity and Regeneration of Woody Species in Qenfot Dry Afromontane Forest, Northeastern Ethiopia. *Abyssinia Journal of Science and Technology*, 7(1), 29-38.

Atkinson, E.E. & Marín-Spiotta E. (2015). Land use legacy effects on structure and composition of subtropical dry forests in St. Croix, US Virgin Islands. *For. Ecol. Manag.*, 335, 270-280. DOI: 10.1016/j.foreco.2014.09.033.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. & Courchamp F. (2012). Impacts of climate change on the future of biodiversity. *Ecol. Lett.*, 15(4), 365-377. DOI: 10.1111/j.1461-0248.2011.01736.x.

Benítez-Malvido, J. (1998). Impact of forest fragmentation on seedling abundance in a tropical rain forest. *Conserv. Biol.*, 12(2), 380–389. DOI: 10.1111/j.1523-1739.1998.96295.x.

Benítez-Malvido, J. & Martínez-Ramos M. (2003). Impact of forest fragmentation on understory plant species richness in Amazonia. *Conserv. Biol.*, 17(2), 389–400. DOI: 10.1046/j.1523-1739.2003.01120.x.

Bentsi-Enchill, F., Damptey, F.G., Pappoe, A., Ekumah, B. & Akotoye H.K. (2022). Impact of anthropogenic disturbance on tree species diversity, vegetation structure and carbon storage potential in an upland evergreen forest of Ghana, West Africa. Trees, *Forests and People,* 8(5), 100238. DOI: 10.1016/j.tfp.2022.100238.

Berhanu, A., Demissew, S., Woldu, Z. & Didita M. (2017). Woody species composition and structure of Kuandisha afromontane forest fragment in northwestern Ethiopia. *J. For. Res.*, 28, 343-355. DOI: 10.1007/s11676-016-0329-8.

Borah, N., Athokpam, F.D., Garkoti, S.C., Das, A.K. & Hore D.K. (2014). Structural and compositional variations in undisturbed and disturbed tropical forests of Bhuban hills in south Assam, India. *International Journal of Biodiversity Science, Ecosystem Services and Managemen*t, 10(1), 9-19. DOI: 10.1080/21513732.2013.873823.

Broadbent, E.N., Asner, G.P., Keller, M., Knapp, D.E., Oliveira, P.J. & Silva J.N.(2008). Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon. *Biol. Conserv.*, 141(7), 1745-1757. DOI: 10.1016/j.biocon.2008.04.024.

Cayuela, L., Benayas, J.M.R. & Echeverría C. (2006). Clearance and fragmentation of tropical montane forests in the Highlands of Chiapas, Mexico (1975–2000). *For. Ecol. Manag.*, 226(1-3), 208-218. DOI: 10.1016/j.foreco.2006.01.047.

Clark, J.S., Beckage, B., Camill, P., Cleveland, B., HilleRisLambers, J., Lichter, J., McLachlan, J., Mohan, J. & Wyckoff P. (1999). Interpreting Recruitment Limitation in Forests. *Am. J. Bot.,* 86(1), 1-16. DOI: 10.2307/2656950.

Cotler, H. & Ortega-Larrocea M.P. (2006). Effects of land use on soil erosion in a tropical dry forest ecosystem, Chamela watershed, Mexico. *Catena*, 65(2), 107-117. DOI: 10.1016/j.catena.2005.11.004.

Dewitte, O., Jones, A., Spaargaren, O., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Michéli, E., Montanarella, L., Thiombiano, L., Van Ranst, E., Yemefack, M. & Zougmoré R. (2013). Harmonisation of the soil map of Africa at the continental scale. *Geoderma*, 211, 138-153. DOI: 10.1016/j.geoderma.2013.07.007.

Durigan, G., Bernacci, L.C., Franco, G.A., Arbocz, G., Metzger, J.P. & Catharino E. (2008). Estádio sucessional e fatores geográficos como determinantes da similaridade florística entre comunidades florestais no Planalto Atlântico, Estado de São Paulo, Brasil. *Acta Botanica Brasilica*, 22, 51-62. DOI: 10.1590/S0102-33062008000100007.

Echeverría, C., Newton, A.C., Lara, A., Benayas, J. & Coomes D.A. (2007). Impacts of forest fragmentation on species composition and forest structure in the temperate landscape of southern Chile. *Glob. Ecol. Biogeogr.*, 16(4), 426-439. DOI: 10.1111/j.1466-8238.2007.00311.x.

Edwards, S., Tadesse, M., Demissew, S. & Hedberg I. (2000). *Flora of Ethiopia and Eritrea*. Vol. 2, Part 1: Magnoliaceae to Flacourtiaceae. Addis Ababa: The National Herbarium.

Edwards, S., Tadesse, M. & Hedberg I. (1995). *Flora of Ethiopia and Eritrea*. Vol. 2, Part 2: Canellaceae to Euphorbiaceae. Addis Ababa: The National Herbarium.

Estoque, R., Dasgupta, R., Winkler, K., Avitabile, V., Johnson, B.A., Myint, S.W., Gao, Y., Ooba, M., Murayama, Y. & D Lasco R. (2022). Spatiotemporal pattern of global forest change over the past 60 years and the forest transition theory. *Environmental Research Letters*, 17, 084022. DOI: 10.1088/1748-9326/ac7df5.

Eyasu, G., Tolera, M. & Negash M. (2020). Woody species composition, structure, and diversity of homegarden agroforestry systems in southern Tigray, Northern Ethiopia. *Heliyon*, 6(12), e05500. DOI: 10.1016/j.heliyon.2020.e05500.

Fahrig, L. (2003). Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology, Evolution, and Systematics*, 34(1), 487-515. DOI: 10.1146/annurev.ecolsys.34.011802.132419.

Fahrig, L. (2020). Why do several small patches hold more species than few large patches? *Glob. Ecol. Biogeogr.*, 29(4), 615-628. DOI: 10.1111/geb.13059.

FAO (2006). NewLocClim. Local climate estimator software and global climate database (version 1.10). Rome.

Fardila, D., Kelly, L.T., Moore, J.L. & McCarthy M.A. (2017). A systematic review reveals changes in where and how we have studied habitat loss and fragmentation over 20 years. *Biol. Conserv*., 212, 130–138. DOI: 10.1016/j.biocon.2017.04.031.

Fashing, P.J., Nguyen, N., Demissew, S., Gizaw, A., Atickem, A., Mekonnen, A., Nurmi, N.O., Kerby, J.T. & Stenseth N.Chr. (2022). Ecology, evolution, and conservation of Ethiopia's biodiversity. *Proc. Natl. Acad. Sci*., 119(50), e2206635119. DOI: 10.1073/pnas.2206635119.

Friis, I. (1992). *Forests and forest trees of Northeast tropical Africa*. Copenhagen: University of Copenhagen.

Friis, I., Demissew, S. & van Breugel P. (2010). *Atlas of the potential vegetation of Ethiopia*. Copenhagen: The Royal Danish Academy of Sciences and Letters.

Gebeyehu, G., Soromessa, T., Bekele, T. & Teketay D. (2019). Species composition, stand structure, and regeneration status of tree species in dry Afromontane forests of Awi Zone, northwestern Ethiopia. *Ecosystem Health and Sustainability,* 5(1), 199-215. DOI: 10.1080/20964129.2019.1664938.

Gebrehiwot, K. & Hundera K. (2014). Species composition, plant community structure and natural regeneration status of Belete moist evergreen montane forest, Oromia regional state, Southwestern Ethiopia. *Momona Ethiopian Journal of Science,* 6(1), 97-101.

Geeraert, L., Aerts, R., Jordaens, K., Dox, I., Wellens, S., Couri, M., Berecha, G. & Honnay O. (2019). Intensification of Ethiopian coffee agroforestry drives impoverishment of the Arabica coffee flower visiting bee and fly communities. *Agrofor. Syst.*, 93, 1729-1739. DOI: 10.1007/s10457-018-0280-0.

Godefroid, S. & Koedam N. (2003). How important are large vs. small forest remnants for the conservation of the woodland flora in an urban context? *Glob. Ecol.* Biogeogr., 12(4), 287-298. DOI: 10.1016/j.biocon.2017.07.007.

Gubila, M., Regassa, A., Legess, G. & Mulatu K. (2024). Land Use Land Cover Change and Its Effect on Selected Soil Physico-Chemical Properties in Southwest Ethiopia. *American Journal of Environmental Science and* Engineering, 12(1), 65-78. DOI: 10.11648/j.ajese.20240803.12.

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sexton, J.O., Austin, M.P., Collins, C.D., Cook, W.M., Damschen, E.I., Ewers, R.M., Foster, B.L., Jenkins, C.N., King, A.J., Laurance, W.F., Levey, D.J., Margules, CH.R., Melbourne, B.A., Nicholls, A.O., Orrock, J.L., Song, D.-X. & Townshend J.R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, 1(2), e1500052. DOI: 10.1126/sciadv.1500052.

Hansen, M.C., Potapov, P.V., Pickens, A.H., Tyukavina, A., Hernandez-Serna, A., Zalles, V., Turubanova, S., Kommareddy, I., Stehman, S.V., Song, X.P. & Kommareddy A. (2022). Global land use extent and dispersion within natural land cover using Landsat data. *Environmental Research Letters*, 17(3), 034050. DOI: 10.1088/1748-9326/ac46ec.

Hansen, M.C., Wang, L., Song, X.P., Tyukavina, A., Turubanova, S., Potapov, P.V. & Stehman S.V. (2020). The fate of tropical forest fragments. *Science Advances*, 6(11), eaax8574. DOI: 10.1126/sciadv.aax8574.

Hedberg, I. & Edwards S. (1989). *Flora of Ethiopia and Eritrea*. Vol. 3. Pittosporaceae to Araliaceae. Addis Ababa: The National Herbarium.

Hedberg, I., Kelbessa, E., Edwards, S., Demissew, S. & Persson E. (2006). *Flora of Ethiopia and Eritrea*. Vol. 5. Gentianaceae to Cyclocheilaceae. Addis Ababa: The National Herbarium.

Hedberg, S., Edwards, S. & Nemomissa S. (2003). *Flora of Ethiopia and Eritrea*. Vol. 4, Part 1. Apiaceae to Dipsacaceae. Addis Ababa: The National Herbarium.

Hending, D., Randrianarison, H., Andriamavosoloarisoa, N., Ranohatra-Hending, C., Holderied, M., McCabe, G. & Cotton S. (2023). Forest fragmentation and its associated edge-effects reduce tree species diversity, size, and structural diversity in Madagascar's transitional forests. *Biodivers. Conserv.*, 32(10), 3329–3353. DOI: 10.1007/s10531-023-02657-0.

Hernandez-Ruedas, M.A., Arroyo-Rodrıguez, V., Meave, J.A., Martínez-Ramos, M., Ibarra-Manríquez, G., Martínez, E., Jamangapé, G., Melo, F.P.L. & Santos B.A. (2014). Conserving Tropical Tree Diversity and Forest Structure: The Value of Small Rainforest Patches in moderately managed landscapes. *PLoS ONE*, 9(6), e98931. DOI: 10.1371/journal.pone.0098931.

Ibáñez, I., Katz, D.S., Peltier, D., Wolf, S.M. & Connor Barrie B.T. (2014). Assessing the integrated effects of landscape fragmentation on plants and plant communities: the challenge of multiprocess–multiresponse dynamics. *J. Ecol.*, 102(4), 882–895. DOI: 10.1111/1365-2745.12223.

Jha, C.S., Goparaju, L., Tripathi, A., Gharai, B., Raghubanshi, A.S. & Singh J.S. (2005). Forest fragmentation and its impact on species diversity: an analysis using remote sensing and GIS. *Biodiver. Conserv.*, 14, 1681-1698. DOI: 10.1007/s10531-004-0695-y.

Kassahun, A.A., Abate, D.F. & Belete D.A. (2024). The effects of disturbance on woody species composition, structure and regeneration status in the ura natural forest, Guangua district, Awi Zone, Ethiopia. *Heliyon*, 10(18). DOI: 10.21203/rs.3.rs-4258401/v2.

Kebebew, Z. & Ozanne C. (2022)3 Woody plant conservation value of three contrasting forest management regimes in Southwest Ethiopia. *Forests*, 13(9), 1438. DOI: 10.3390/f13091438.

Kefalew, A., Soromessa, T. & Demissew S. (2022). Plant diversity and community analysis of Sele-Nono forest, Southwest Ethiopia: implication for conservation planning. *Botanical Studies*, 63(1), 23. DOI: 10.1186/s40529-022-00353-w.

Kent, M. (2012). *Vegetation description and data analysis: a practical approach*. John Wiley & Sons.

Kim, D.H., Sexton, J.O. & Townshend J.R. (2015). Accelerated deforestation in the humid tropics from the 1990s to the 2000s. *Geophysical Research Letters*, 42(9), 3495-3501. DOI: 10.1002/2014GL062777.

Kuma, M. & Shibru S. (2015). Floristic composition, vegetation structure, and regeneration status of woody plant species of oda forest of humbo carbon project, wolaita, Ethiopia. *Journal of Botany*, 5(1), 963816. DOI: 10.1155/2015/963816

Laurance, W.F. (2008). Theory meets reality: How habitat fragmentation research has transcended island biogeographic theory. *Biol. Conserv.*, 141(7), 1731-1744. DOI: 10.1016/j.biocon.2008.05.011.

Lemenih, M. (2024). Review of the Historic Trajectory of Deforestation, its Drivers and Implications in Ethiopia. DOI: 10.20944/preprints202401.0332.v1.

Lewis, S.L., Edwards, D.P. & Galbraith D. (2015). Increasing human dominance of tropical forests. *Science*, 349(6250), 827-832. DOI: 10.1126/science.aaa99.

Ma, J., Li, J., Wu, W. & Liu J.(2023). Global forest fragmentation change from 2000 to 2020. *Nature Communications*, 14(1), 3752. DOI: 10.1038/s41467-023-39221-x.

Ma, L., Huang, M., Shen, Y., Cao, H., Wu, L., Ye, H., Lin, G. & Wang Z. (2015). Species diversity and community structure in forest fragments of Guangzhou, South China. *J. Trop. For. Sci.*, 27, 148–157.

MacArthur, R.H. & Wilson E.O. (1967). *The theory of island biogeography*. Princeton: Princeton University Press.

Majumdar, K. & Datta B.K. (2016). Effects of patch size, disturbances on diversity and structural traits of tropical semi-evergreen forest in the lowland Indo Burma hotspot: implication on conservation of the threatened tree species. *Journal of Mountain Science*, 13, 1397–1410. DOI: 10.1007/s11629-015-3686-4.

Malcolm, J.R., Valenta, K. & Lehman S.M. (2017). Edge effects in tropical dry forests of Madagascar: additivity or synergy? *Landsc. Ecol.*, 32, 327-341. DOI: 10.1007/s10980-016-0453-z.

Malik, Z.A. & Bhatt A.B. (2016). Regeneration status of tree species and survival of their seedlings in Kedarnath Wildlife Sanctuary and its adjoining areas in Western Himalaya, India. *Tropical Ecology*, 57(4), 677-690.

Masha, M., Bojago, E., Belayneh, M., Tadila, G. & Abera A. (2024). Quantifying forest degradation rates and their drivers in Alle district, southwestern Ethiopia: Implications for sustainable forest management practices. *Geomatica*, 76(2). DOI: 10.1016/j.geomat.2024.100009.

Maua, J.O., MugatsiaTsingalia, H., Cheboiwo, J. & Odee D. (2020). Population structure and regeneration status of woody species in a remnant tropical forest: A case study of South Nandi forest, Kenya. *Global Ecology and Conservation*, 2, 00820. DOI: 10.1016/j.gecco.2019.e00820.

McFarland, B.J. (2018). *The Context of Tropical Rainforest Deforestation and Degradation*. In Conservation of Tropical Rainforests. Palgrave Studies in Environmental Policy and Regulation. Cham: Palgrave Macmillan. DOI:10.1007/978-3-319-63236-0_2.

Mengist, W., Soromessa, T. & Feyisa G.L. (2022). Forest fragmentation in a forest Biosphere Reserve: Implications for the sustainability of natural habitats and forest management policy in Ethiopia. *Resources, Environment and Sustainability*, 80. DOI: 10.1016/j.resenv.2022.100058.

Mohandass, D. & Davidar P. (2010). The relationship between area, and vegetation structure and diversity in montane forest (shola) patches in southern India. *Plant Ecology and Diversity*, 3(1), 67-76. DOI: 10.1080/17550874.2010.492843

Mulatu, K., Hundera, K. & Senbeta F. (2024) Analysis of land use/land cover changes and landscape fragmentation in the Baro-Akobo Basin, Southwestern Ethiopia. *Heliyon*, 10(7). DOI: 10.1016/j.heliyon.2024.e28378.

Mulatu, K., Hundera, K. & Senbeta, F. (2025). Analysis of Forest Cover Change in the Southwest Ethiopia: Key Drivers, Impacts, and Conservation Implications. *International Journal of Forestry Research*, 2025(1), 5523008. DOI: 10.1155/ijfr/5523008.

Muluneh, M.G., Feyissa, M.T. & Wolde T.M. (2021). Effect of forest fragmentation and disturbance on diversity and structure of woody species in dry Afromontane forests of northern Ethiopia. *Biodiver. Conserv.*, 30(6), 1753-1779. DOI: 10.1007/s10531-021-02167-x.

Pao, N.T. & Upadhaya K. (2017). Effect of fragmentation and anthropogenic disturbances on floristic composition and structure of subtropical broad leaved humid forest in Meghalaya, Northeast India. *Applied Ecology and Environmental Research.*, 15(385). DOI: 10.15666/aeer/1504_385407.

Pradhan, A., Ormsby, A. & Behera N. (2018). Diversity, population structure, and regeneration potential of tree species in five sacred forests of western Odisha, India. *Écoscience*, 26(1), 85-97. DOI: 10.1080/11956860.2018.1522148.

Rahman, M.M. (2023). Impact of habitat fragmentation on the Diversity of Flora and Fauna of Bangladesh. *SSRN Electronic Journa*l. DOI:10.2139/ssrn.4451469

Raj, A., Jhariya, M., Khan, N., Nema, S., Devi, A. & Ghanshyam (2022). Effect of Deforestation and Forest Fragmentation on Ecosystem Services. In P. Panwar, G. Shukla, J. Bhat & S. Chakravarty (Eds.), *Land Degradation Neutrality: Achieving SDG 15 by Forest Management* (pp. 25-41). Singapore: Springer Nature. DOI: 10.1007/978-981-19-5478-8_2

Rajamurugan, J., Mohandass, D., Campbell, M.C., Jayakrishnan, P., Balachandran, N. & Shao S.C. (2021). Fragmentation causes woody plant composition decline in sacred grove patches in the Puducherry region of southeast India. *Applied Ecology and Environmental Research*, 19(3). DOI: 10.15666/aeer/1903_16251643.

Rajamurugan, J., Mohandass, D., Jayakrishnan, P., Ramesh, R., Muthukumaran, N. & Arunpandi A. (2017). Impact of fragment size on woody species richness and abundance of scared groves in south- east India. In *National seminar "Biodiversity Conservation and Sustainable Utilization"* (pp. 41). Bharathiar University: Department of Botany.

Ratner, B. (2009). The correlation coefficient: Its values range between+1/−1, or do they?. *Journal of Targeting, Measurement and Analysis for Marketing*, 17(2), 139-142. DOI: 10.1057/jt.2009.5.

Razafindratsima, O.H., Brown, K.A., Carvalho, F., Johnson, S.E., Wright, P.C. & Dunham A.E. (2018). Edge effects on components of diversity and above-ground biomass in a tropical rainforest. *J. Appl. Ecol.*, 55(2), 977-985. DOI: 10.1111/1365-2664.12985.

Sahana, M., Sajjad, H. & Ahmed R. (2015). Assessing spatio-temporal health of forest cover using forest canopy density model and forest fragmentation approach in Sundarban reserve forest, India. *Modeling Earth Systems and Environment*, 1, 49. DOI: 10.1007/s40808-015-0043-0.

Schmitt, C.B. (2006). *Montane rainforest with wild Coffea arabica in the Bonga region (SW Ethiopia): plant diversity, wild coffee management and implications for conservation.* Ecology and Development Series, No. 48. Göttingen: Cuvillier Verlag.

Schoener, T.W. (2010). The MacArthur-Wilson equilibrium model. A chronicle of what it said and how it was tested. In J.B. Los & R.E. Ricklefs (Eds.), *The Theory of Island Biogeography Revisited*. Princeton: Princeton University Press.

Senbeta, F. & Denich M. (2006). Effects of wild coffee management on species diversity in the Afromontane rainforests of Ethiopia. *For. Ecol. Manag.*, 232(1-3), 68-74. DOI: 10.1016/j.foreco.2006.05.064.

Senbeta, F., Schmitt, C., Woldemariam, T., Boehmer, H.J. & Denich M. (2014). Plant diversity, vegetation structure and relationship between plant communities and environmental variables in the Afromontane Forests of Ethiopia. *Sinet: Ethiopian Journal of Science*, 37(2), 113-130.

Sewale, B. & Mammo S .(2022). Analysis of floristic composition and plant community types in Kenech Natural Forest, Kaffa Zone, Ethiopia. *Trees, Forests, and People*, 7. DOI: 10.1016/j.tfp.2021.100170.

Singh, M., Shahina, N., Das, S., Arshad, A., Siril, S., Barman, D. et al. (2022). Forest Resources of the World: Present Status and Future Prospects. In P. Panwar, G. Shukla, J.A. Bhat & S. Chakravarty (Eds.), *Land Degradation Neutrality: Achieving SDG 15 by Forest Management*. Singapore: Springer Nature.

Slattery, Z. & Fenner R. (2021). Spatial analysis of the drivers, characteristics, and effects of forest fragmentation. *Sustainability*, 13(6), 3246. DOI: 10.3390/su13063246.

Soomers, H., Karssenberg, D., Verhoeven, J.T.A., Verweij, P.A. & Wassen M.J. (2013). The effect of habitat fragmentation and abiotic factors on fen plant occurrence. *Biodivers. Conserv.*, 22, 405–424. DOI: 10.1007/s10531-012-0420-1.

Sukumar, R., Dattaraja, H.S., Suresh, H.S., Radhakrishnan. J., Vasudeva, R., Nirmala, S. & Joshi N.V. (1992). Long-term monitoring of vegetation in a tropical deciduous forest in Mudumalai, southern India. *Curr. Sci.,* 62(9), 608-616.

Tadesse, G., Zavaleta, E. & Shennan C. (2014). Coffee landscapes as refugia for native woody biodiversity as forest loss continues in southwest Ethiopia. *Biol. Conserv.*, 169, 384-391. DOI: 10.1016/j.biocon.2013.11.034.

Tadesse, M., Alemu, B., Bekele, G., Tebikew, T., Chamberlin, J. & Benson T. (2006). *Atlas of the Ethiopian rural economy.* Washington, Addis Ababa: International Food Policy Research Institute (IFPRI) and Central Statistical Agency and Ethiopian Development Research Institute. DOI: 10.2499/0896291545.

Taubert, F., Fischer, R., Groeneveld, J., Lehmann, S., Müller, M.S., Rödig, E., Wiegand, T. & Huth A. (2018). Global patterns of tropical forest fragmentation. *Nature*, 554(7693), 519-522. DOI: 10.1038/nature25508.

Temesgen, F.& Warkineh B. (2020). Woody species structure and regeneration status in kafta sheraro national park dry forest, Tigray region, Ethiopia. *International Journal of Forestry Research*, (1), 4597456. DOI: 10.1155/2020/4597456.

Tripathi, O.P. & Reynald K.R. (2010). Effect of forest fragment size on tree diversity and population structure of humid subtropical forest of Meghalaya, India. *Biodiversity Science*, 18(2), 208–214. DOI: 10.3724/SP.J.1003.2010.222.

Tripathi, O.P., Upadhaya, K., Tripathi, R.S. & Pandey H.N. (2010). Diversity, dominance and population structure of tree species along fragment-size gradient of a subtropical humid forest of northeast India. *Research Journal of Environmental and Earth Science*, 2(2), 97-105.

Vellend, M., Verheyen, K., Jacquemyn, H., Kolb, A., Van Calster, H., Peterken, G. & Hermy M. (2006). Extinction debt of forest plants persists for more than a century following habitat fragmentation. *Ecology*, 87(3), 542-548. DOI: 10.1890/05-1182.

Wekesa, C., Kirui, B.K., Maranga, E.K., Muturi, G.M. (2019). Variations in forest structure, tree species diversity and above-ground biomass in edges to interior cores of fragmented forest patches of Taita Hills, Kenya. *For. Ecol. Manag.*, 440, 48-60. DOI: 10.1016/j.foreco.2019.03.011.

Wiersum, K.F. (2010). Forest dynamics in Southwest Ethiopia: interfaces between ecological degradation and resource enrichment. In F. Bongers & T. Tennigkeit (Eds.), *Degraded forests in Eastern Africa: management and restoration.* Routledge.

Wood, A., Tolera, M., Snell, M., O'Hara, P. & Hailu A. (2019). Community forest management (CFM) in south-west Ethiopia: Maintaining forests, biodiversity and carbon stocks to support wild coffee conservation. *Global Environmental Change*, 59, 101980. DOI: 10.1016/j.gloenvcha.2019.101980.

Appendix 1. List of woody species in study forest fragments.

Species	Family	Life form	Status in FFSs			
			VL	L	M	S
Acanthus polystachyus Delile	Acanthaceae	S	+	+	+	-
Albizia gummifera (J.F.Gmil.) GA.Sm.	Fabaceae	T	+	+	-	+
Albizia schimperiana Oliv	Fabaceae	T	+	+	+	+
Allophylus abyssinica (Hochst)	Sapindaceae	T	+	-	+	+
Apodytes dimidata E.Mey. ex Arn.	Icacinaceae	T	+	+	+	+
Asparagus africana Lam	Asparagaceae	L	+	+	+	+
Baphia abyssinica Brummitt	Fabaceae	T	+	+	+	+
Bersama abyssinica Fresen	Melianthaceae	T	+	+	+	-
Bothrocline schmperi olive & Hiern	Asteraceae	T	+	+	-	+
Bridelia micrantha Hochst.Baill.	Phyllanthaceae	T	-	+	+	+
Brucea antidysenterica J.F.Mill.	Simaroubaceae	T	+	+	+	-
Cassipourea malosana (Baker) Alston	Rhizophoraceae	T	+	-	-	-
Clausena anisata (Willd.) Hook. F. ex Benth	Rutaceae	T	+	+	+	+
Clematis longicaudata Steud ex A. Rich.	Ranunculaceae	L	+	-	-	+
Coffea arabica L.	Rubiaceae	S	+	+	+	-
Combretum panciculatum Vent.	Combretaceae	L	+	-	-	-
Cordia african Lam	Boraginaceae	T	+	+	-	+
Croton macrostachyus Del.	Euphorbiaceae	T	+	+	+	+
Cyathea manniana Hook	Cyatheaceae	T	+	+	+	+
Deinbollia kilimandscharica Taub	Sapindaceae	T	+	+	-	-
Dombeya torrida (J.F. Gmel.) Bamps	Malvaceae	T	+	+	-	-
Draceana fragrans (L.) Ker Gawl	Asparagaceae	T	-	+	-	-
Draceana stedudneri Engl.	Asparagaceae	T	+	+	-	+
Ehretia cymosa Thonn	Boraginaceae	T	+	+	+	+
Ekebergia capensis Sparm	Meliaceae	T	+	+	+	+
Elaeodendron buchananii (Loes.) Loes.	Celastraceae	T	-	+	+	-
Embelia schimperi Vatke	Myrsinaceae	S	+	+	+	+
Erythrina brucei Schweinf	Fabaceae	T	+	+	+	+
Erythrococca abyssinica Pax	Euphorbiaceae	S	+	+	-	+
Erythrococca trichogyne (Muell Arg.) Prain	Euphorbiaceae	S	+	+	-	+
Euphorbia abyssinica Gmel.	Euphorbiaceae	S	+	+	-	+
Ficus plamata forssk.	Euphorbiaceae	T	+	+	+	+
Ficus vasta Vahl	Moraceae	T	+	+	+	+
Galiniera saxifraga (Hochst.) Bridson	Rubiaceae	T	+	+	+	+
Hagenia abyssinica (Willd.)	Rosaceae	T	+	-	-	-
Hippocratea goetzei Loes	Celastraceae	L	+	+	+	+
Hipporatea african (Willd.) Loes. ex Engl.	Celastraceae	L	+	+	-	-
Ilex mitis (L.) Radlk	Aquifoliaceae.	T	+	+	+	+
Juniperus procera Hocht. ex. Endl.	Cupressaceae	T	-	+	-	-
Justicia schimperiana T.Anderson	Acanthaceae	S	-	+	+	-
Landolphia buchananii (Hallier f.) Stapf	Apocynaceae	L	+	+	+	-
Lepidotrichilia volkensii (Gürke) J.-F.Leroy	Meliaceae	T	+	+	-	-
Macaranga capensis (Baill) Sim	Euphorbiaceae	T	+	+	+	+
Maesa lanceolata Forssk.	Myrsinaceae	T	+	+	+	+
Manilkara butugi Chiov	Sapotaceae	T	+	+	+	+
Maytenus graulipes (Welw. ex Olive.)	Celastraceae	T	+	+	+	+
Millettia ferruginea (Hochst.) Hochst. ex Baker	Fabaceae	T	+	+	+	+
Olea capensis subsp	Oleaceae	T	+	+	+	+
Oncinotis tenuiloba Stapf.	Apocynaceae	L	+	-	+	-
Pavetta abyssinica Fresen.	Rubiaceae	T	+	+	-	-
Premna schimperi Engl.	Rubiaceae	T	+	+	+	-
Pavonia urens Cav.	Malvaceae	S	+	-	-	-
Phoenx reclinata Jacq.	Arecaceae	T	+	+	+	+
Phyllanthus reticulatus Poir.	Euphorbiaceae	S	+	-	-	-
Phytolacca dodecandra L'Herit.	Phytolaccaceae	L	+	+	-	-
Pittosporum virdiflorum Sims	Pittosporaceae	T	+	+	+	+
Polyscias fulva (Hiern.) Harms	Araliaceae	T	+	+	+	+
Pouteria adolfi-friederici (Engl.) Baehni	Sapotaceae	T	+	-	+	+
Prunus africana (Hook. F.) kalkm	Rosaceae	T	+	+	+	+
Psychotria nervosa Swartz	Rubiaceae	S	+	+	+	+
Rhamnus prinoides L'Herit	Rhamnaceae	S	+	+	+	+
Ricinus communis L.	Euphorbiaceae	S	+	-	+	-
Rytigyna neglecta (Hiern) Robyns	Rubiaceae	T	+	+	+	+
Sapium ellipticum (Hochst.) Pax	Euphorbiaceae	T	-	+	+	-
Schefflera abyssinica (Hochst. ex A.Rich.) Harms	Araliaceae	T	+	+	+	+
Sida urens L	Malvaceae	S	+	-	-	-
Solanecio gigas (Vatke) C. Jeffrey	Asteraceae	S	-	+	+	+
Solanecio mannii (Hook f.) Jeffery	Asteraceae	S	+	+	+	+
Solanum anguivai Lam.	Solanaceae	S	+	-	-	+
Solanum gigantum Jacq.	Solanaceae	T	+	-	+	-
Spatoda nilotica P.Beauv.	Bignoniaceae	T	+	-	-	-
Syzygium guineense (Willd.) DC.	Myrtaceae	T	+	+	+	+
Tacazzea conferta N.E.Br.	Apocynaceae	L	+	+	-	+
Tiliacora troupinii Curod.	Menispermacee	L	+	-	+	+
Trichilia dregeana Sond	Meliaceae	T	+	+	+	+
Trichilia emeitica Vahl	Meliaceae	T	+	-	+	-
Trilepisium madagascarinace DC.	Moraceae	T	+	-	-	+
Triumfetta semitriloba Jacq.	Malvaceae	S	+	+	+	+
Triumfetta srhomboidea Jacq	Malvaceae	S	+	-	+	-
Urera hypselodendron (A. Rich.) Wedd.	Urticaceae	L	+	+	+	-
Vepris dainellii (Pichi-serm) Kokwara	Rutaceae	T	+	+	+	-
Vernonia amygdalina Del. in Caill.	Asteraceae	S	+	+	+	+
Vernonia auriculifera Hiern	Asteraceae	S	+	+	+	+

(+) represent presence and (-) absence. For FFS: VL for Very Large, L for Large, M for Medium, and S for Small. For life form: T for tree, S for shrubs and L for lianas.