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Articles

Woody species diversity, structure, and carbon stock in a disturbed Dry Afromontane Forest in Ethiopia

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Abstract - Ethiopia is one of the tropical countries endowed with diverse forest formations. These forests supply the largest proportions of wood used for furniture, construction, and household energy consumption. Arbagugu forest is one of the Dry Afromontane forests under severe anthropogenic disturbances. Despite this fact, up to date information is lacking about the status of the forest. This study evaluates the woody species composition, diversity, population structure, and carbon stock in Arbagugu forest. We found that the forest had low woody species richness and diversity. Many woody species had inadequate regeneration status. The carbon stock density of the forest falls below values reported for other similar forests. Therefore, it is important to develop forest management strategies, utilization plans, and restoration initiatives that meet the local community's interest. Minimizing anthropogenic disturbances is essential for preserving plant diversity and enhancing carbon storage in the forest. Our study recommends restoration of highly degraded areas through enrichment plantings and protection measures along with investments in awareness-raising about forest conservation. We also recommend further research quantifying the socio-ecological impacts of human activities on the forest and investigating the potential for sustainable timber harvesting using selected tree species from the forest.

Diversidade de espécies lenhosas, estrutura e estoque de carbono em uma Floresta Afromontana seca e perturbada na Etiópia

Resumo - A Etiópia é um país tropical dotado de diversas formações florestais. Estas florestas fornecem as maiores proporções de madeira utilizada para mobiliário, construção e consumo doméstico de energia. A floresta de Arbagugu é uma das florestas secas afromontanas sob graves perturbações antrópicas. Apesar disso, faltam informações atualizadas sobre o estado atual da floresta. Este estudo avalia a composição, diversidade, estrutura da comunidade e estoques de carbono de espécies lenhosas na floresta de Arbagugu. A floresta de Arbagugu apresenta baixa riqueza e diversidade de espécies e a regeneração de algumas espécies arbóreas é inadequada. A densidade do estoque de carbono cai abaixo dos valores relatados para outras florestas similares. Portanto, é importante desenvolver estratégias de manejo florestal, planos de utilização e iniciativas de restauração que atendam aos interesses da comunidade local. Minimizar as perturbações antrópicas também é fundamental para preservar a diversidade das plantas e aumentar o armazenamento de carbono na floresta. Recomendamos plantios de enriquecimento e medidas de proteção em áreas altamente degradadas e investimentos para conscientização sobre a conservação florestal. Recomendamos, também, pesquisas que quantifiquem os impactos socioecológicos das atividades humanas na floresta e investiguem o potencial para a colheita sustentável de madeira utilizando espécies de árvores selecionadas.

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Introduction

Tropical forests are home to half of the earth's biodiversity, containing about 40% of global terrestrial carbon, and presenting an essential influence on the Global Climate System (Pan et al., 2011; Devaraju et al., 2015; Lewis et al., 2015). These forests cover about 7% of the land surface and are habitat to more than half of the world's biotic species (Gallery, 2014). Tropical forests help rural food security through different non-timber forest resources (food, medicines, and fibers) collected as a sustainable livelihood (Roberts et al., 2018). Furthermore, these forests provide fuel-wood for an estimated 2.4 billion rural people in less developed countries and the main material for the houses of at least 1.3 billion people worldwide (Rametsteiner & Whiteman, 2014). According to a number of studies, a large number of people in developing countries depend on forests as a source of income, livelihoods, and well-being (Muller et al., 2018; Roberts et al., 2018).

Ethiopia has close to 17.35 million ha (15.7%) forest resources, including bamboo, dense woodland, plantations, and natural forests (Bekele et al., 2015; Franks et al., 2017). These forests provide wood for construction, furniture, household energy, and wood-based industries (Teketay, 2001) and played a significant role in the national economy. According to Nune et al. (2013), the economic contribution of these forests to the national gross domestic product (GDP) was estimated at 18.8 % in 2012/13. Generally, the forests in Ethiopia exhibit a higher structural complexity and community composition variability resulting from the diverse biophysical, social conditions, and disturbance history (Teketay et al., 2010).

The dry evergreen Afromontane forest is among the forest vegetation types widely dispersed in the central, south-eastern, eastern, northern, and southern highlands in Ethiopia (Friis et al., 2010). This forest has been identified as a threatened forest ecosystem category that is under the concern of degradation and deforestation (Lemenih & Bongers, 2011). Reports indicated that the deforestation rate amounted to 92,000 ha^{-1} yr^{-1}, while, new plantation area establishment is about 18,000 ha^{-1} yr^{-1} for the period 2000-2013 in Ethiopia (Moges et al., 2010). Overall, agricultural expansion (both subsistence and commercial), fuel-wood consumption, illegal logging, and forest fire are the major anthropogenic drivers of deforestation and forest degradation in Ethiopia (Bekele et al., 2015). Studies revealed that anthropogenic disturbances induce changes in the woody community composition, structure, and carbon stock in different types of forests in Ethiopia (Yohannes et al., 2015; Kidane et al., 2016; Shiferaw et al., 2019). Furthermore, the effect of land-use change on woody species distribution and carbon stock is one of the main topics studied on the ecology of tropical forests (Van Gemerden et al., 2003; Conti et al., 2014; Tadesse et al., 2014).

Arbagugu forest is one of the dry Afromontane forests designated as one of the National Forest Priority Areas (NFPAs) in the country (Ethiopian Forestry Action Program, 1994). This forest has a history of selective logging and has been exposed to various types of anthropogenic disturbances, including seasonal grazing, uncontrolled burning, wood collection, and new settlements accompanied by agricultural expansion (Hassen, 2013). Additionally, the forest is a controlled hunting area for the mountain Nyala (*Tragelaphus buxtoni*) population (Evangelista et al., 2007).

A recent study in Arbagugu forest has revealed a higher rate of deforestation over the past 29 years (1986-2015), with an annual rate of 1.4% (Yahya et al., 2020). Various studies have documented the impact of anthropogenic disturbances on the species composition, structure, and carbon stock potential of various forests, highlighting the importance of understanding these factors for effective management and conservation (e.g. Mishra et al., 2004; Addo-Fordjour et al., 2009). Despite this fact, there was no systematic study to understand the diversity, structure, and carbon storage of the Arbagugu forest. This information is crucial for assessing its status and developing a comprehensive management and restoration plan (Ssegawa & Nkuutu, 2006). In this study, we conducted a comprehensive assessment of the Arbagugu forest, focusing on the woody species composition, diversity, community structure (characterized by density, basal area, and regeneration status), and carbon stock in both above-and below-ground biomass. We framed the study around the following key research questions: 1) How are the woody species composition, diversity, and regeneration status of trees in Arbagugu forest under severe anthropogenic disturbances? 2) What is the carbon storage capacity of this forest ecosystem under heavy anthropogenic disturbances? The insights gained from addressing these questions will enhance our understanding of how anthropogenic disturbances affect the forest ecosystem and will enable the development of appropriate interventions for Arbagugu and other similar dry Afromontane forests in Ethiopia.

Material and methods

Study site description

Arbagugu forest is found 279 km in the southeast of Addis Ababa, the capital city of Ethiopia (Yahya et al., 2020). The forest is predominantly confined in Aseko, Chole, Gololcha, Guna, and Merti administrative districts in East Arsi Zone (Figure 1). Geographically, the forest is located between 8˚15' to 8˚16 N and 5˚14 to 5˚39' E. The study area topography is characterized by hills and plateaus, with an elevation range of 1,500 to 3,200 m. The area has a bimodal rainfall distribution pattern, with the main rainy season from July to September, and a less pronounced short rainy season from March to June (Figure 2). Analyzing 10 years of data, the study area received an average annual rainfall of 1,424 mm, and has an average annual temperature of 14.7 °C. According to Nigussie (2014), the dominant soil type of the landscape is Nitosol and Cambisol. The forest belongs to dry evergreen Afromontane and sub-afro-alpine forest classification (Friis et al., 2010).

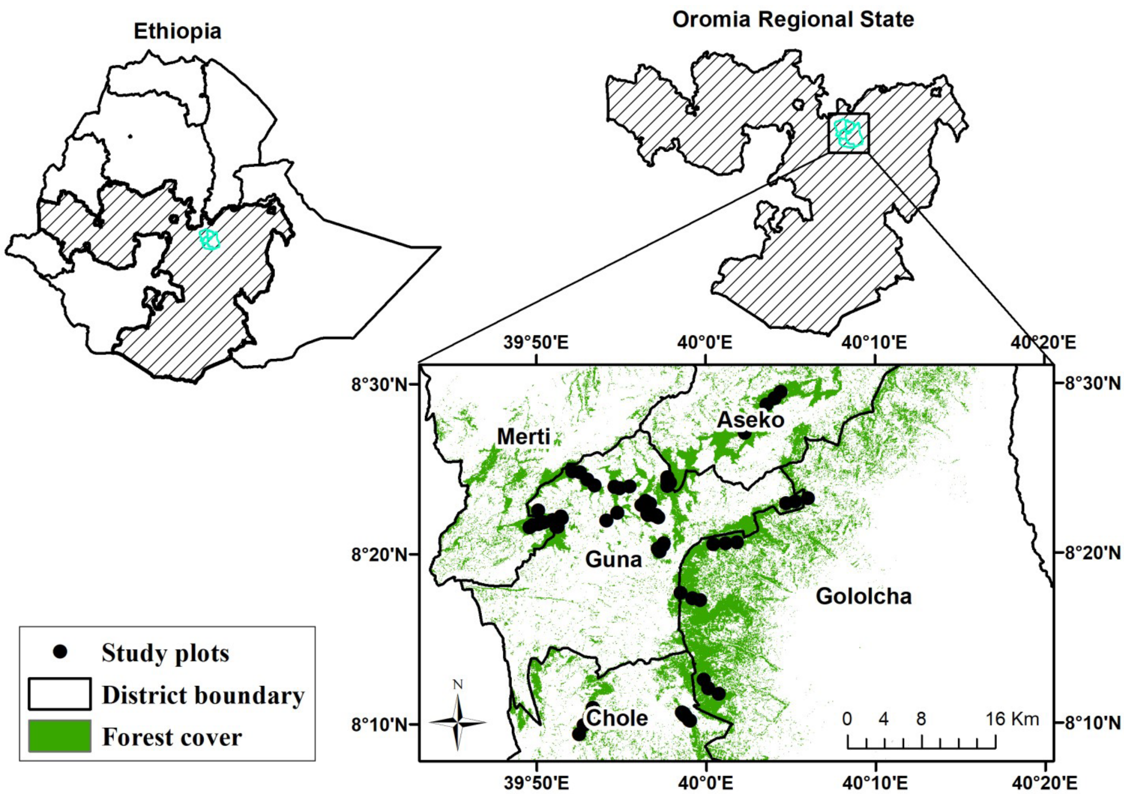

Figure 1. Map of the study area.

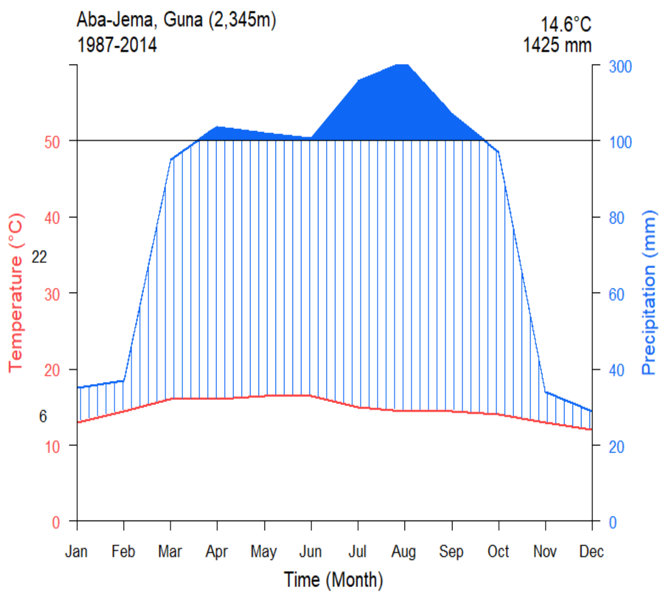

Figure 2. Climate diagram indicating mean annual temperature and the mean annual precipitation for the years 1987 to 2014. The temperature and precipitation data were obtained from the National Meteorology Agency of Ethiopia (Aba-Jema town in Guna Meteorological station about 18 km from the Arbagugu forest).

Fonte: Walter & Lieth (1967).

Land-use history

The Arbagugu forest was once a dense forest, serving as a primary source of wood, grazing land, and game reserve for the local community (Hassen 2013). Historically, the forest covered a total area of 34,173 ha, with 99% (30,000 ha) covered with natural forest and 1% (4,173 ha) covered with plantation forests. During the imperial era (before 1975), the state controlled a portion of the forest, while a significant portion was granted to war veterans and state officials (Hassen 2013). The grantees, including war veterans, state officials, and their families cleared the forest to create new arable land and generate income from the sale of logs. Additionally, six foreigners owned sawmills were established around the forest, leading to unrestricted harvesting of tree species and a significant reduction in forest area coverage. Despite these activities, none of the grantees and sawmill owners contributed to the protection and development of the forest. This has had severe consequences for the forest's ecosystem and biodiversity.

In 1975, the nationalization of land led to the allocation of private forest lands to peasant associations. This marked the beginning of the Arbagugu State Forest Protection and Development Project. The forest was recovering from the past unrestricted deforestation, but destruction continued until the project reorganized its structure and took control of the forest from the peasant associations in 1982 (Hassen 2013). For example, between 1983 and 1992, the forest lost 2,657.25 ha due to agricultural land expansion (80%), fire (15%), and other factors (5%). In response to this decline, the government designated the forest as one of the National Forest Priority Areas (NFPA) in Ethiopia (EFAP 1994). Subsequently, large areas of plantation forests were established around the forest, and it was eventually considered as a protected forest. Currently, the forest is under the administration of the Oromiya Forest and Wildlife Enterprise (OFWE). However, despite these efforts, the forest remains vulnerable to anthropogenic disturbances, including free grazing, fire, farmland expansion, settlement, and illegal logging (Figure 3).

Forest inventory

A reconnaissance survey was undertaken in the Arbagugu forest to assess general forest conditions and decide the data collection approach. Overall, the natural forests in Aseko, Chole, Gololcha, Guna, and Merti administrative districts were surveyed in December 2017. A systematic and non-random sampling procedure was employed to collect the vegetation data. Transect lines were laid parallel to the edge of the forest in the East-West orientation. Three to five sample plots were established at 300 m intervals along each transect line. Overall, fifty-three sample plots (20 × 100 m) were established. In each sample plot, the diameter at breast height (DBH) and the total height of all tree species and saplings were measured using a diameter tape, Vertex III hypsometer (Haglöf Sweden AB, Långsele, Sweden), and a graduated height measuring wood. Seedlings were counted in the subplots (20 × 20 m) established at the center of each sample plot. The local names of all trees, saplings and seedlings were recorded and identified to the species level in the field following the Flora of Ethiopia and Eritrea publications

(Hedberg et al., 1989, 2003, 2004; Edwards et al., 1995). For those species difficult to identify in the field, leaf samples were collected, pressed, and identified at the National Herbarium, Addis Ababa University. The Angiosperm Phylogeny Group IV (Group et al., 2016) was also used to classify species into families. The spatial location (latitude and longitude) and elevation of each sample plot was measured using Garmin GPS-72 receiver.

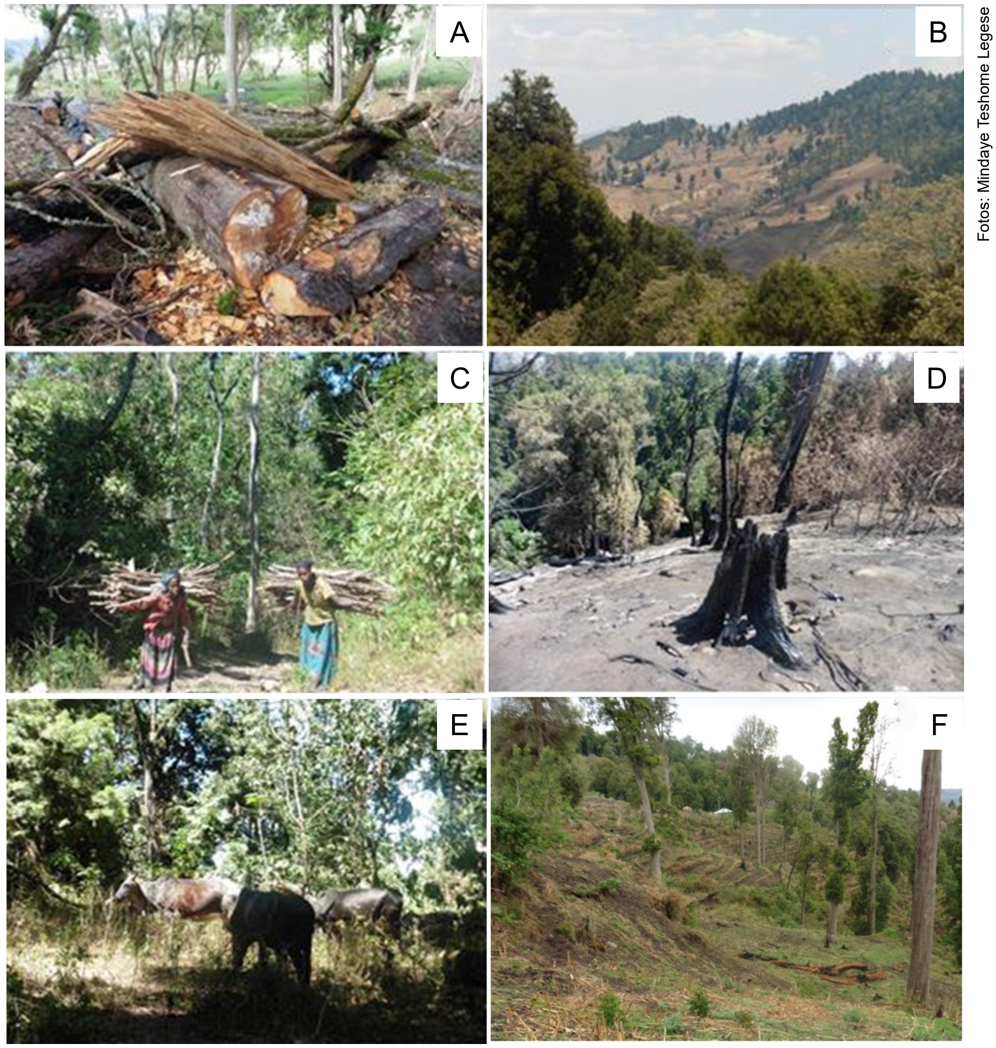

Figure 3. The observed anthropogenic disturbances in Arbagugu forest. (A) illegal logging; (B) farmland expansion; (C) firewood collection; (D) forest fire; (E) free grazing; (F) temporary settlement.

Data Analysis

Woody species composition, structure, and diversity

Individual woody species were categorized into mature trees (DBH ≥ 5 cm), saplings (height ≥ 1.3 m and 2.5 ≤ DBH < 5.0 cm), and seedlings (0.30 ≤ height < 1.30 m and DBH ≤ 2.5 cm) following Lamprecht classification (Lamprecht, 1989). All woody species with DBH ≥ 2.0 cm were considered to describe the structure and diversity of the forest. The density (stem ha^{-1}), basal area (m^2 ha^{-1}), and importance value index (IVI) were also calculated for each species. The density was calculated by converting the total number of individuals of each species per plot to equivalent numbers per hectare. The relative density of each species was calculated as the number of individuals of each species per hectare divided by the total number of all species. The relative frequency was obtained by dividing the number of plots in which the species was recorded by the total number of plots established in the study area. The relative dominance of a species was obtained by dividing the total basal area of each species by the total basal area of all species. Finally, the importance value index(IVI) was determined by summing the relative density, relative dominance, and relative frequency values (Kent & Coker, 1992). The proportional analysis of the IVI allowed us to assess the relative contribution of each species in the study area and the most important species were those having the highest IVI values (Gonçalves et al., 2017). The taxonomic diversity and species distribution of the forest were also determined by using Shannon-Wiener (Equation 1) and Pielou's evenness (Equation 2) indices following the procedures in Magurran (2004).

$$H' = -\sum_{i=1}^{s} (p_i * \ln p_i) \quad \text{(Equation 1)}$$

where H' is the Shannon-Wiener diversity index, pi is the proportion of individuals found in the i^{th} species, and ln is the natural logarithm.

$$J' = \frac{H'}{H'_{\max}} \quad \text{(Equation 2)}$$

where J' is Pielou's evenness index, H' is the Shannon-Wiener diversity index, and H'_{max} is the natural logarithm of the total number of woody species identified in the study area.

The species richness was estimated by using individual-based rarefaction for seedlings, saplings, and mature trees (Chao et al., 2014), which were computed using the 'iNEXT' package (Hsieh et al., 2016) based on 100 replicate bootstrapping runs to estimate 95% confidence intervals (e.g. Rodrigues et al., 2019). Whenever the 95% confidence intervals did not overlap, species numbers differed significantly at $p < 0.05$ (Colwell et al., 2012). We used individual-based rarefaction because the number of sample plots may vary for each regeneration status, which may bring bias on the estimation of species richness (Monge-González et al., 2020). Rarefaction was estimated as the mean of individual-based rarefaction curves.

To compare changes in woody species composition based on regeneration status (seedlings, saplings, and mature trees) a non-metric multidimensional scaling (NMDS) analysis was performed using the '*metaMDS*' function (Oksanen et al., 2018). Thus, after checking the stress generated by the NMDS, we corroborate the non-metric fit based on stress using linear regression and selected the Euclidean distance method (Oksanen et al., 2018).

We also used a permutational multivariate analysis of variance (PERMANOVA, 999 permutations) to determine significant differences in woody species composition among seedlings, saplings, and mature trees (Oksanen et al., 2018) followed by a posterior pairwise Adonis test (Arbizu-Martinez, 2019). All different functions of NMDS are available within the "vegan" package (Oksanen et al., 2018).

Regeneration status

The density of seedlings, saplings, and mature trees was calculated. The regeneration status was determined by comparing the density of seedlings, saplings, and matured trees following the method described in Khan et al. (1987). Specifically, good regeneration is characterized by a higher density of seedlings compared to saplings, which in turn are denser than mature trees. Fair regeneration is indicated when the density of seedlings is equal to or greater than that of saplings, and both are equal to or greater than the density of mature trees. Poor regeneration occurs when a species only survives in the sapling stage, but not in seedling or mature tree stages. Finally, we consider a species lacks regeneration if it only exists as mature trees, with no seedlings or saplings present.

Biomass and carbon stock

The aboveground biomass (AGB) of individual tree species (DBH > 5 cm) was estimated using the general pan-tropical allometric equation developed by Chave et al. (2014) for tropical dry forests (Equation 3). The equation shows the relationships between above ground biomass, diameter at 1.3 m above ground level (DBH), total height, and wood density.

$$AGB = 0.0673\ (\rho \times DBH^2 \times H)^{0.976} \quad \text{(Equation 3)}$$

where AGB is aboveground biomass (in kg), DBH is the diameter at 1.3 m above ground level (cm), H is the total height (m), and ρ is wood density (g cm^{-3}).

The wood density data were obtained from the global wood density database (Zanne et al., 2009), the African wood density database (Carsan et al., 2012), and from a recent publication of Tesfaye et al. (2019). The below-ground biomass (BGB) was calculated from the obtained above-ground biomass by considering a shoot/root ratio of 0.26 (Cairns et al., 1997). The total biomass was obtained by summing up the aboveground and belowground biomass and converted into carbon by multiplying the estimated value by 0.47 (Eggleston et al., 2006). The total carbon stock was converted into tons of CO_2 equivalent by multiplying the value by 3.67 (Pearson, 2007).

Results

Woody community composition and diversity

A total of 37 woody species belonging to 25 families were recorded in the Arbagugu forest (Table 1). Among the identified woody species *Podocarpus falcatus*, *Juniperus procera*, *Olea europaea.* subsp. *cuspidata*, *Hagenea abyssinica*, *Allophylus abyssinicus, Euphorbia amplophylla*, and *Pavetta abyssinica* are locally used for timber. The most species-rich families were *Euphorbiaceae* (represented by three species), *Araliaceae*, *Celastraceae*, *Flacourtiaceae*, *Meliaceae*, *Rosaceae*, *Rubiaceae*, and *Sapindaceae* (each presented two species). The remaining sixteen families were represented only by one tree species. The overall Shannon-Wiener diversity and evenness values were 2.58 and 0.70, respectively. Species richness differed significantly between seedlings, saplings, and mature trees using individual-based rarefaction curves (Figure 4A). More specifically, we observed that the species richness with the number of individuals was higher in mature trees, and up to twice higher than the seedlings. The non-metric multidimensional scaling (NMDS) revealed that woody species composition showed differences between all regeneration status and despite the overlap between seedling and samplings significant differences remain according to the pairwise Adonis test (Figure 4B).

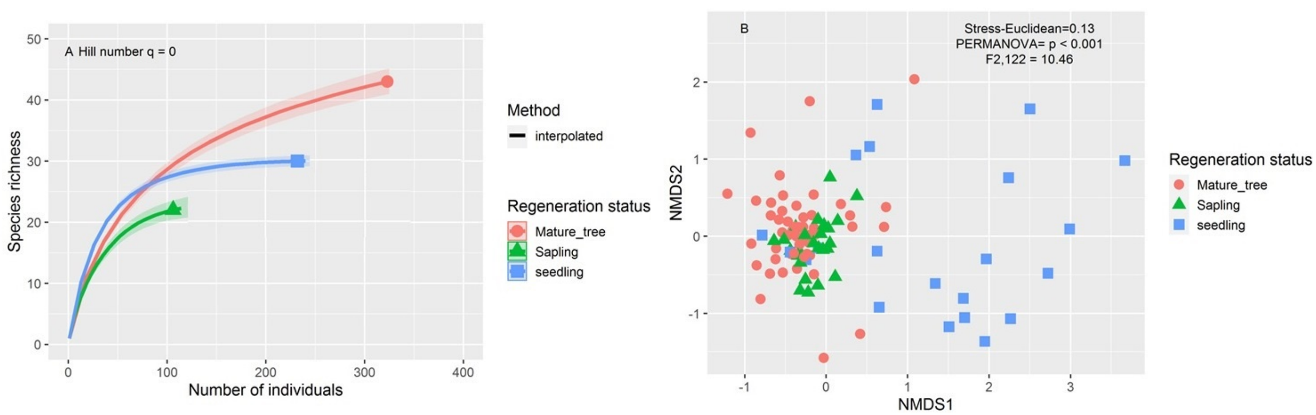

Figure 4. (A) Rarefaction curve, and (B) non-metric multidimensional scaling (NMDS) plots that show the differences in woody species composition among the seedlings, saplings, and mature trees in Arbagugu forest.

The density of seedlings, saplings, and matured trees were 1,174, 101, and 84 stems ha^{-1}, respectively. The highest density of mature tree species was recorded for *Podocarpus falcatus*, followed by *Juniperus procera*, *Schefflera volkensii*, *Croton macrostachyus*, and *Maesa lanceolata*, which together accounted for 73% of the total mature tree density (Table 2). The total basal area of the tree species with DBH ≥ 2.0 cm was 21.3 m^2 ha^{-1}. *Podocarpus falcatus* was the dominant tree species comprising 44.5% of the total basal area followed by *Juniperus procera* (41.3%), *Schefflera abyssinica* (3%), *Schefflera volkensii* (1.5%), and *Prunus africana* (1.3%). The top five most important tree species based on the IVI values were *Podocarpus falcatus* (31.5%), *Juniperus procera* (21.5%), *Osyris quadripartite* (7.6%), *Croton macrostachys* (3.9%), and *Maesa lanceolata* (2.6%).

Table 1. Scientific names, frequency (Freq.), density (stems ha^{-1}), basal area (m^2 ha^{-1}), and importance value index (IVI) of tree species >2 cm diameter recorded from Arbagugu forest in descending order of IVI values.

Rank	Scientific name	Family	Habit	Density	Freq.	BA	IVI
1	*Podocarpus falcatus* (Thunb.) Mirb.	Podocarpaceae	T	42.15	0.2	9.48	31.49
2	*Juniperus procera* Hochst.	Cupressaceae	T	13.88	1.41	8.80	21.49
3	*Osyris quadripartita* Decne.	Santalaceae	S	0.3	4.53	0.01	7.63
4	*Croton macrostachys* Del.	Euphorbiaceae	T	3.02	1.41	0.22	3.85
5	*Maesa lanceolata* Forssk.	Myrsinaceae	T	3.52	0.6	0.16	2.61
6	*Cassipourea malosana* (Baker) Alston	Rhizophoraceae	S	1.91	0.91	0.04	2.30
7	*Lepidotrichilia volkensii* (Gurke) Leroy	Meliaceae	S/T	0.7	1.11	0.01	2.12
8	*Allophyllus abyssinicus* (Hochest.) Radlk.	Sapindaceae	T	1.11	0.8	0.21	2.10
9	*Celtis africana* Burm. f.	Ulmaceae	T	1.51	0.7	0.19	2.05
10	*Psydrax schimperiana* (A. Rich.) Bridson	Rubiaceae	T	0.5	1.01	0.04	1.92
11	*Maytenes senegalensis* (Lam.) Exell	Celastraceae	T	2.21	0.4	0.12	1.71
12	*Schefflera abyssinica* Harms.	Araliaceae	T	0.4	0.3	0.63	1.64
13	*Maytenus undata* (Thunb.) Blackelock	Celastraceae	S/T	1.61	0.5	0.05	1.53
14	*Teclea nobilis* Del.	Rutaceae	T	2.72	0.2	0.06	1.47
15	*Schefflera volkensii* (Engl.) Harms	Araliaceae	T	0.8	0.3	0.33	1.33
16	*Olinia rochetiana* A. Juss.	Oliniaceae	T	0.6	0.5	0.12	1.25
17	*Vernonia auriculifera* Hiern	Asteraceae	T	0.6	0.5	0.00	1.07
18	*Prunus africana* (Hook. f.) Kalkm.	Rosaceae	T	0.7	0.2	0.27	1.03
19	*Nuxia congesta* K. Br. ex Fresen.	Loganiaceae	T	0.6	0.4	0.06	0.99
20	*Bersama abyssinica* Fresen.	Melianthaceae	T	0.7	0.4	0.00	0.94
21	*Ekbergia capensis* Sparrm.	Meliaceae	T	0.7	0.3	0.10	0.94
22	*Rhus glutinosa* A. Rich.	Anacardiaceae	T	0.5	0.4	0.03	0.91
23	*Rytigynia neglecta* (Hiern) Robyns	Rubiaceae	S/T	0.6	0.4	0.00	0.91
24	*Calpurnia aurea* (Ait.) Benth	Fabaceae	S	0.5	0.4	0.00	0.86
25	*Olea europaea.* subsp.*cuspidata* (Wall. & G. Don) Cif.	Oleaceae	T	0.91	0.1	0.15	0.76
26	*Ochna inermis* Schweinf. ex Penzig	Ochnaceae	S	0.2	0.4	0.00	0.75
27	*Doviyalis verrucosa* (Hochst.) Warb.	Flacourtiaceae	S	0.5	0.3	0.01	0.72
28	*Zanha golungensis* Hiern	Sapindaceae	T	0.8	0.1	0.03	0.52
29	*Canthium oligocarpum* Hiern	Rubiaceae	S/T	0.3	0.2	0.04	0.52
30	*Celtis* spp.	Ulmaceae	S/T	0.3	0.2	0.01	0.46
31	*Euphorbia amplophylla* Pax	Euphorbiaceae	T	0.2	0.2	0.02	0.44
32	*Dovyalis abyssinica* (A.Rich.) Warb.	Flacourtiaceae	S/T	0.2	0.2	0.00	0.41
33	*Clutia abyssinica* Jaub. & Spach.	Euphorbiaceae	S	0.2	0.1	0.08	0.37
34	*Ficus vallis-choudae* Del	Moraceae	T	0.2	0.1	0.02	0.27
35	*Pavetta abyssinica* Fresen.	Rubiaceae	S	0.2	0.1	0.00	0.25
36	*Hagenea abyssinica* I. F. Gmel.	Rosaceae	T	0.1	0.1	0.00	0.21
37	*Brucea antidysenterica* J. F. Mill.	Simaroubaceae	S/T	0.1	0.1	0.00	0.21

T =tree, S/T = shrub or tree, and S = shrub.

Regeneration status

The identified tree species in the study area exhibited a considerable variation in regeneration status (Table 2). Eleven tree species (31%) exhibited good regeneration, while seven tree species (20%) showed no regeneration. Additionally, a total of 14 tree species (40%) exhibited fair regeneration status, including the dominant timber species *Juniperus procera* and *Podocarpus falcatus*. In contrast, three tree species (9%) exhibited poor regeneration status. Notably, no new tree species were recorded in the study area during this research (Table 2).

Table 2. List of regenerating tree species, vernacular names, family, and their regeneration status in Arbagugu forest.

Nº	Scientific name	Family	Se	Sa	Mt	Se/Sa	Sa/Mt	RS
1	*Lepidotrichilia volkensii* (Gurke) Leroy	Meliaceae	21	4	1.0	5.1	4.00	GR
2	*Canthium oligocarpum* Hiern	Rubiaceae	6	5	0.0	1.2	0.00	GR
3	*Doviyalis verrucosa* (Hochst.) Warb.	Flacourtiaceae	24	3	0.0	7.8	-	GR
4	*Calpurnia aurea* (Ait.) Benth	Fabaceae	13	1	0.0	13.2	-	GR
5	*Maesa lanceolata* Forssk.	Myrsinaceae	26	4	3.0	6.6	1.33	GR
6	*Maytenes senegalensis* (Lam.) Exell	Celastraceae	379	5	1.0	75.9	5.00	GR
7	*Allophylus abyssinicus* (Hochest.) Radlkofer.	Sapindaceae	60	3	1.0	20.1	3.00	GR
8	*Celtis africana* Burm. f.	Ulmaceae	47	2	1.0	23.5	2.00	GR
9	*Galinera saxifrage* (Hochst.) Bridson	Rubiaceae	90	1	0.0	89.7	-	GR
10	*Prunus africana* Kalkm.	Rosaceae	21	4	0.9	5.1	4.44	GR
11	*Maytenus undata* (Thunb.) Blackelock	Celastraceae	91	20	1.2	4.6	16.5	GR
12	*Scolopia theifolia* Gilg	Flacourtiaceae	43	2	2.0	21.3	1.00	FR
13	*Podocarpus falcatus* (Thunb.) Mirb.	Podocarpaceae	37	36	46.2	1	0.78	FR
14	*Juniperus procera* Hochst.	Cupressaceae	7	1	10.0	7.4	0.10	FR
15	*Croton macrostachyus* Del.	Euphorbiaceae	9	1	4.0	8.8	0.25	FR
16	*Cassipourea malosana* (Baker) Alston	Rhizophoraceae	60	1	2.0	60.3	0.50	FR
17	*Olea europaea.* subsp.*cuspidata* (Wall. & G. Don) Cif.	Oleaceae	16	1	1.0	16.2	1.00	FR
18	*Ekebergia capensis* Sparrm.	Meliaceae	4	-	1.0	-	0.00	FR
19	*Olinia rochetiana* A. Juss.	Oliniaceae	13	-	0.5	-	0.00	FR
20	*Rhus* spp.	Anacardiaceae	74	-	0.0	-	0.00	FR
21	*Zanha golungensis* Hiern	Sapindaceae	-	1	0.7	-	1.48	FR
22	*Psydrax schimperiana* (A. Rich.) Bridson	Rubiaceae	1	1	0.4	1.5	2.66	FR
23	*Pavetta abyssinica* Fresen.	Rubiaceae	126	-	0.0	-	-	FR
24	*Pittosporum viridiflorum* Sims	Pittosporaceae	1	-	0.2	-	0.00	FR
25	*Osyris quadripartita* Decen.	Santalaceae	3	-	0.4	-	0.00	FR
26	*Brucea antidysenterica* J.F. Mill.	Simaroubaceae	-	1	0.0	-	-	PR
27	*Bersama abyssinica* Fresen.	Melianthaceae	-	3	0.6	-	5.00	PR
28	*Vernonia auriculifera* Hiern	Asteraceae	-	1	0.5	-	2.22	PR
29	*Nuxia congesta* K. Br. ex Fresen.	Loganiaceae	-	-	0.5	-	0.00	NR
30	*Schefflera abyssinica* Harms.	Araliaceae	-	-	0.8	-	0.00	NR
31	*Rhus glutinosa* A. Rich.	Anacardiaceae	-	-	0.4	-	0.00	NR
32	*Clutia abyssinica* Jaub. & Spach.	Euphorbiaceae	-	-	1.0	-	0.00	NR
33	*Euphorbia amplophylla* Pax	Euphorbiaceae	-	-	1.0	-	0.00	NR
34	*Ficus vallis-choudae* Del	Moraceae	-	-	1.0	-	0.00	NR
35	*Hagenea abyssinica* I. F. Gmel.	Rosaceae	-	-	1.0	-	0.00	NR

Where Se = seedlings/ha, Sa = saplings/ha, Mt = mature trees/ha, Se: Sa = seedling to Sapling ratio, Sa: Mt = sapling to mature tree ratio, RS = regeneration status, GR= good regeneration, FR = fair regeneration, PR = poor regeneration, and NR=no regeneration.

Biomass and carbon stock

The total biomass ranged between 12.53 and 1,671.2 Mg ha^{-1} with a mean value of 355.4 Mg ha^{-1} in the Arbagugu forest. About 81% of the total biomass was contained in aboveground vegetation, whereas 19% was contained in the below ground. The total carbon stock (aboveground and belowground) ranged between 6.3 Mg C ha^{-1} and 835.6 Mg C ha^{-1} with a mean value of 177.7 Mg C ha^{-1}. This value is equivalent to 652.16 Mg CO_2 eq. ha^{-1}. Among the trees *Juniperus procera*, *Podocarpus falcatus*, *Prunus africana*, *Schefflera abyssinica*, and *Olea africana* subsp. *cuspidata* contributed 95.7% of the total aboveground biomass and carbon stock.

Discussion

This study examined the woody species composition, structure, biomass, and carbon stock potential in the Arbagugu forest, which have been affected by various human-induced disturbances. The forest had low woody species composition and diversity. Moreover, many tree species had inadequate regeneration status, and stored a lower carbon stock compared to other dry Afromontane forests. These findings highlight the urgent need for conservation and forest restoration efforts by local authorities, conservation practitioners, and other stakeholders to preserve the Arbagugu forest and enhance the ecosystem goods and services it provides.

Woody species composition and diversity

The woody species richness recorded in this study area is lower than those reported from other similar dry Afromontane forests in Ethiopia, including the Wof-Washa forest (Fisaha et al., 2013), Yegof forest (Woldearegay et al., 2018), Jibat forest (Bekele, 1993), and Egdu forest (Tilahun et al., 2011). However, our findings are relatively similar to those findings reported in the Chilimo forest (Siraj, 2019), Gedo forest (Kebede et al., 2014), Awi zone forest (Gebeyehu et al., 2019b), and Yerer mountain forest (Yahya et al., 2019). This suggests that our study area may have a limited number of tree species compared to these other forests but is comparable to some others.

The Shannon-Wiener diversity index in the present study area is lower than those reported from the Wof-Washa forest (Yirga et al., 2019) and the Zengena forest (Tadele et al., 2014). However, it is higher than the findings from the Yegof forest (Woldearegay et al., 2018) and Yerer Mountain forest (Yahya et al., 2019). The observed variation in species composition and diversity may be attributed to the differences in the magnitude of anthropogenic disturbances (Evangelista et al., 2007; Mallie & Abraham, 2018). Our study area, the Arbagugu forest, is heavily affected by anthropogenic disturbances such as free grazing, fire, farmland expansion, illegal logging, and settlement (Figure 3). It is well established that anthropogenic disturbances can impact plant diversity by removing woody species, creating gaps, and reducing canopy cover (Kikoti & Mligo, 2015).The removal of woody species and the creation of gaps can lead to a reduction in tree density and canopy cover, ultimately affecting plant diversity. In our study area, the high level of anthropogenic disturbance may be responsible for the lower Shannon-Wiener diversity index compared to other forests with fewer disturbances.

The mean densities of trees in this study area are higher than those reported from other similar dry Afromontane forests in Ethiopia, including the Wof-Washa forest (Yirga et al., 2019), Awi zone forest (Gebeyehu et al., 2019b), and Chilimo forest (Siraj, 2019). However, our study's mean basal area of 21.3 m^2 ha^{-1} is lower than that found in the Denkoro forest (Ayalew, 2003) and Gedeo forest (Kebede et al., 2014). This suggests that our study site may have a higher density of trees, but a smaller overall area of tree coverage compared to these other forests. The relatively lower mean basal area may be attributed to the historical logging of larger diameter trees in the Arbagugu forest (Ethiopian Forestry Action Program, 1994; Hassen, 2013). Previous studies have reported lower basal area and tree density in dry Afromontane forests that have experienced anthropogenic disturbances in central Ethiopia (Bekele, 1993; Tilahun et al., 2011; Siraj, 2019). Our findings suggest that the Arbagugu forest may have been similarly affected by human activities, leading to a reduction in its overall tree cover.

Regeneration status

The characteristic tree species of the dry Afromontane Forest, including *Podocarpus falcatus, Juniperus procera,* and *Olea europaea* subsp. *cuspidata* exhibited a relatively fair regeneration status. In contrast, the less abundant species such as *Lepidotrichilia volkensii, Canthium oligocarpum, Dovyalis verrucosa, Calpurnia aurea,* and *Maesa lanceolata* showed better regeneration status (Table 1). The observed fair regeneration status of these trees may be attributed to the persistent occurrence of fires, which eliminates the accumulated litter and exposes the mineral soil, releasing nutrients for seedlings to grow (Sharew et al., 1997). Some tree species such as *Polyscias fulva, Schefflera abyssinica, Erythrina brucei,* and *Apodytes dimidiata* lacks regeneration and this pattern has been previously reported from various dry Afromontane forests in Ethiopia (Teketay, 2005; Tesfaye et al., 2010; Abiyu et al., 2013; Tadele et al., 2014). This may be attributed to the absence of suitable microsites for seed germination, the lack of a persistent seed bank, seed predation, and free grazing by livestock (Teketay, 2005; Abiyu et al., 2013; Kikoti & Mligo, 2015). This could have significant implications for the future existence of these tree species, potentially altering the vegetation composition and affecting the ecological and economic functions of the forest. Our findings revealed a significant variation in the number of tree species represented by seedlings, saplings, and mature trees within the study area (Figure 4). Notably, the highest number of tree species was recorded at the seedling stage (24 species) and the sapling stage (22 species). This abundance can likely be attributed to increased sunlight intensity on the forest floor, resulting from the observed anthropogenic disturbances or gap formations within Arbagugu forest. These conditions create a favorable environment for the recruitment and growth of seedlings into saplings.

The mean densities of seedlings and saplings in this study were lower than those reported by other similar dry Afromontane forests in Ethiopia (Girma & Mosandl, 2012; Kebede et al., 2014). This disparity is likely due to the differences in anthropogenic disturbance. The present study area is affected by various types of human activities (Figure 3). Various studies highlighted the impact of anthropogenic disturbances such as fire and grazing on seedling survival and growth (Wassie et al., 2009; Kikoti & Mligo, 2015; Giday et al., 2018). The local community uses the forest as their communal grazing land during the dry period, which involves removing whole plants or parts of the vegetative or reproductive structures, as well as trampling of the soil surface by animals. This results in seedling mortality and soil compaction, limiting recruitment and seedling establishment (Teketay, 2005). The free grazing practice in different forests of Ethiopia has been reported to affect the survival and growth of tree seedlings (Wassie et al., 2009). It is essential to develop alternative livestock feeding systems, such as cut and carry systems or barn feeding, to avoid the negative impacts of free grazing practices. This would help to promote the regeneration and survival of tree seedlings in the forest.

Biomass and carbon stock

The mean biomass (355.4 Mg ha^{-1}) and carbon stock (177.7 Mg C ha^{-1}) estimate of the present study was lower than the findings reported from different tropical forests including the closed-canopy forests from Africa (Lewis et al., 2013), the South African Mistbelt forest (Mensah et al., 2016), Chilimo dry Afromontane forest (Siraj, 2019), Awi zone forest (Gebeyehu et al., 2019a), and Ziquala monastery forest (Girma et al., 2014) in Ethiopia. This variation may be due to the difference in the disturbance level, stand density, and the number of larger diameter trees, which constituted a significant amount of biomass. In line with this, Brown & Lugo (1990) stated that the total amount of biomass in forest ecosystems might differ with variation in biophysical characteristics, microclimate, and anthropogenic disturbance levels. During the imperial era, parts of the Arbagugu forest have been given to loyal and dignitary state officials. They cleared the forest in search of arable land, selectively harvested commercially important timber trees, and deforested the forest area (Hassen, 2013). During this period, seven sawmills with a daily production capacity of 15 m^3 were established at the periphery of the forest and they were functioning until 1991. The partly decomposed tree stumps observed on the Arbagugu forest grounds revealed the selective harvesting of larger diameter trees in the past, which in turn resulted in lower biomass stock today. Among the recorded trees, only two tree species namely *Podocarpus falcatus* and *Juniperus procera* contributed the largest proportion over 85% of the aboveground biomass and carbon stock. These two tree species are also the most widely used timber trees by the local communities. The findings suggest that preserving the most abundant and larger tree species that are less impacted by human disturbances can be an effective way to store large amounts of carbon within the forest. This is consistent with research from other regions, including the moist forests of Tanzania (McNicol et al., 2018) and Central African moist forests (Bastin et al., 2015).

Conclusions

The results of this study demonstrated Arbagugu forest had a low number of woody species composition and diversity. Moreover, many tree species had inadequate regeneration status, and stored a lower amount of carbon stock compared to other dry Afromontane forests in Ethiopia. These findings highlight the urgent need for conservation and forest restoration efforts by local authorities, conservation practitioners, and other stakeholders to preserve the Arbagugu forest and enhance the ecosystem goods and services it provides. Therefore, it is important to develop forest management strategies and restoration initiatives that meet the local community's interest. Minimizing anthropogenic disturbances is also critical for preserving plant diversity and enhancing carbon storage in the forest. We recommended restoration of highly degraded areas through enrichment plantings and protection measures along with investments in awareness-raising about forest conservation. We also recommend further research quantifying the socio-ecological impacts of human activities on the forest and investigating the potential for sustainable timber harvesting using selected tree species from the forest.

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Conflict of interest

The authors have no conflict of interest to declare

Authors' Contributions

Mindaye Teshome: Conceptualization, investigation, formal analysis, methodology, writing original draft, review and editing.**Nesibu Yahya**: conceptualization, investigation, methodology, writing original draft, review and editing. **Carlos Moreira Miquelino Eleto Torres**: investigation, formal analysis, methodology, supervision, review and editing. **Pedro Manuel Villa Villa**: formal analysis, methodology, review and editing. **Mehari Alebachew**: investigation, formal analysis, methodology, supervision, review and editing.

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