DOI 10.37045/aslh-2024-0004 Acta Silvatica et Lignaria Hungarica, Vol. 20, Nr. 2 (2024) 55–70

Changes in Structure, Tree Species Composition, and Diversity of the Abu Geili Riverine Forest Reserve, Sinnar State, Sudan

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ARTICLE INFO

Keywords:
Trees species diversity
AbuGeili forest conservation
Biodiversity indices analysis
Forest ecosystem management

ABSTRACT

This study assesses the structure, composition, diversity, and conservation status of the Abu Geili Riverine Forest Reserve (AGRFR), Sudan, to evaluate changes in these attributes between 2011 and 2021. Thirty sample plots (radius = 17.84 m) were established systematically. The distance between plots was 50 m and 100 m between survey lines to facilitate the identification, counting, and measuring of diameter at breast height (DBH) and height of all living trees and compare that with 2011 data. The results identified 462 trees across 32 species and 15 families in 2021, reflecting an increase in species and family diversity from 2011, which reported 626 trees from 23 species and 12 families. The Fabaceae family was most dominant, with ten species in 2021 and six in 2011. In both years, the Miliaceae and Moraceae had three species each. Three of the four calculated diversity indices displayed increasing trends, highlighting the rich diversity of the area and its importance for conservation and management.

TANULMÁNY INFÓ

Kulcsszavak:
Fafaj diverzitás
AbuGeili erdőrezervátum
Biodiverzitás index elemzés
Erdei ökoszisztéma kezelés

KIVONAT

Változások a szerkezetben, a fajösszetételben és a diverzitásban az Abu Geili Folyómenti Erdőrezervátumban (Szinnár állam, Szudán). A tanulmány célja a szudáni AbuGeili folyóparti erdőrezervátum (AGRFR) szerkezetének, összetételének, sokféleségének és védettségi helyzetének felmérése, valamint e jellemzők 2011 és 2021 közötti változásainak értékelése. Harminc mintaterületet (Sugár = 17,84 m) alakítottak ki rendszeresen. A parcellák közötti távolság 50 m, a felmérési vonalak közötti távolság 100 m volt, hogy azonosítani lehessen, megszámoljuk és megmérjük a mellmagassági átmérőt (DBH) famagasságit minden élő fa esetében, és összehasonlítsuk a 2011-es adatokkal. Az eredmények azt mutatják, hogy 2021-ben 32 fajból és 15 családból 462 fa volt, ami tükrözi a fajok és a családok sokféleségének növekedését 2011-hez képest, amikor 23 faj és 12 család 626 fájáról számoltak be. A Fabaceae család volt a legdominánsabb, 2021-ben tíz, 2011-ben pedig hat faj. Mindkét évben a Miliaceae és a Moraceae három-három fajjal rendelkezett. A négy kiszámított diverzitási indexből három növekvő trendet mutatott, kiemelve a terület gazdag diverzitását és fontosságát a megőrzés és a kezelés szempontjából.

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1 INTRODUCTION

The vital role of forests in maintaining ecological balance, supporting economic growth, and providing livelihoods is undeniable, as highlighted by UNEP, 2007; Rajasugunasekar et al., 2023; Serbouti et al., 2023; Musa et al., 2024 and the Food and Agriculture Organization (FAO 2009a). Tropical forests are biodiversity hotspots that contain about 70 % of all animal and plant species despite covering only 7% of the Earth's dry surface area (Ulyshen et al., 2023; Debebe et al., 2023). Such biodiversity is crucial for fundamental ecological processes and the survival of many species. Yet, these ecosystems face significant threats from deforestation and forest degradation, driven by the immense pressure from human activities and natural factors. Forest degradation leads to species extinction and reduced diversity; however, it also decreases primary productivity.

The Sahel's trees and shrubs are vital to combating desertification, providing many useful products, and maintaining the natural ecosystem (Lu et al., 2023; Rajasugunasekar et al., 2023). The role of indigenous fruit trees in food security and nutrition, especially in semi-arid regions, is increasingly recognized. Similarly, the AGRFR in Sudan, characterized by its low rainfall savanna woodland, has seen the introduction of diverse species, both exotic and native, making it a significant area for biodiversity within the tropical forest ecosystem (FAO, 2010; IUCN, 2010; Yasin and Mulyana, 2022).

However, forest managers face challenges aligning national goals with forest-level management plans amid global emphasis on timber production and biodiversity conservation, carbon sequestration, and providing wildlife habitats and amenities (Elsiddig, 2002). Transforming these goals into actionable strategies is complex and is exacerbated by the increasing human population and land use changes, including agricultural expansion, increased livestock density, and altered fire regimes and fallow periods (Ouedraogo et al., 2010; Alcamo et al., 2011; Oke and Jamala, 2013). These changes threaten forest structure, composition, and biodiversity, necessitating management interventions to preserve and enhance their conservation value and sustainability (Kumar et al., 2006).

Tree species inventory and diversity studies are pivotal in understanding trends in structure, composition, and diversity (Yakubu et al., 2020). Such information is crucial for conservation efforts, yet the documentation of trees and shrubs in areas like the Abu Geili Riverine Forest Reserve is lacking. Despite the significance of these ecosystems, only a few studies have focused on tree diversity in the natural forests of the Blue Nile state and the Tozi natural forest in Sinnar state (Mohammed et al., 2021a; Dafa-Alla et al., 2022; Yasin and Mulyana, 2022).

This study assesses the structure, composition, diversity, and conservation status of the AGRFR and evaluates changes in these attributes between 2011 and 2021. Additionally, it provides information to assist policymakers and resource management planners in creating effective strategies to manage and sustain these crucial ecosystems.

2 MATERIALS AND METHODS

2.1 Description of the study area

The study was conducted in the AGRFR, Sudan, between latitude 13°34'41.51" N and longitude 33°35'20.08" E (*Figure 1*). The AGRFR is a tropical dry forest, covering a total area of about 807 feddans (338.94 hectares) with original species such as *Acacia nilotica*, *Balanities aegyptiaca*, *Acacia seyal*, *Acacia nubic*, and *Capparis decidua*. New species such as Eucalyptus spp, Khaya spp., Moringa oleifera, bamboo spp, and others were introduced after the forest was designated as a reserved area on August 18, 1940, and registered in Gazeta No. 1. The vegetation cover of the AGRFR primarily consists of *Acacia nilotica* in a pure stand located in the flood basin in the northern part. In contrast, the southern part of the forest predominantly features other species, such as *Eucalyptus spp*. and *Khaya senegalensis*. This area also includes small experimental plots of *Sclerocarya birrea*, *Albizia lebbek*, *Dalbergia melanoxylon*, *Moringa oleifera*, and *Cordia africana*, all intermingled within the Eucalyptus plots. Additionally, the forest hosts a small nursery and a mango tree garden. Clumps of bamboo are present along the river bank. Many species grow in the Gerif land, including *Faidherbia albida*, *Calotropis procera*, *Maytenus senegalensis*, *Boscia senegalensis*, and *Cordia rothii*. *Capparis decidua* and *Acacia seyal* are also present outside the basin in the Karab site, featuring a mix of planted and naturally occurring tree species. The primary objectives of the forest are timber production including sawn timber and fuel wood and the conservation of tree and shrub biodiversity. The government controls the area through the Forests National Corporation of Sinnar State. Villages surround the forest, bordered to the north by Kandwat, to the east by Al-Tekina and Abu Geili, and to the west and south by the Blue Nile. Despite its importance, the AGRFR faces several challenges from human activities such as agricultural expansion, livestock overgrazing, and firewood collection, all of which threaten the ecosystem’s balance. Regulated forestry including selective logging and the planting of exotic species local uses such as harvesting construction wood and fuel and gathering non-timber products like medicinal plants and livestock fodder have all influenced the forest’s structure and diversity over the decades. However, illegal logging and farmland expansion have significantly degraded the reserve, altering its ecological dynamics and necessitating robust conservation efforts to maintain forest health. The soil of the area is classified as dark cracking clay soil (vertisol) in the “Mayaa” site, sand and gravel (eroded slopes) soil in the Karab slopes, and permeable silt deposits soil in the Gerif slopes (Fahmi, 2017). The AGRFR was already extremely degraded and some part of AGRFR was already converted to farmlands while a portion has been designated for the plantation of exotic species such as *Khaya senegalensis, Tectona grandis, Eucalyptus camaldulensis,* and *Dalbergia sisso*. The wet season in the study area is between June and October, while the dry season is from November to April. Annual rainfall ranges from 450 to 750 mm, with annual temperatures varying from (31˚C) in April to (22˚C.) in January and relative humidity from 78–80 % in August to 8–9 % in March (Abdelrahim, 2015; Mohammed et al., 2021a; Gurashi, 2022; Yasin and Mulyana, 2022).

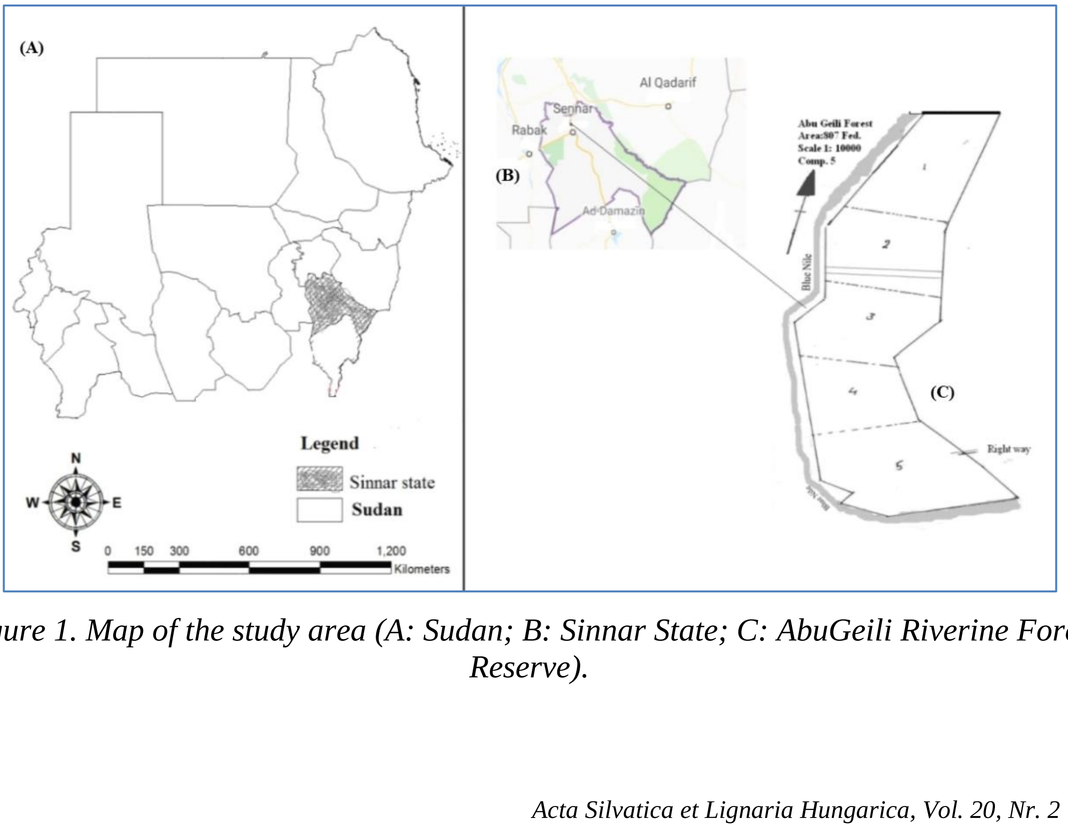

Figure 1. Map of the study area (A: Sudan; B: Sinnar State; C: AbuGeili Riverine Forest Reserve).

2.2 Data collection

Data collection was conducted in two phases; the Forest National Corporation (FNC) Sinnar state conducted the first in 2011, collecting data by establishing 30 circular sampling plots (Radius 17.84 m = 0.1 ha), which were determined in the systematic sampling grid using ArcGIS software. The second data collection phase was conducted in February–May 2021 using the same sample plots and procedure to assess the structure, composition, diversity, and conservation status of AGRFR and evaluate changes in these attributes between 2011 and 2021. The grid consisted of several parallel survey lines spaced 100 m apart, and the distance between each sample plot was 50 m. Where 30 % of sample plots were placed in a degraded stand (low diversity, e.g., one or two species) and 70 % in a non-degraded stand (high diversity, e.g., more than two species), ensuring the representativeness of the sample plots. A survey method to assess the species composition that used a 0.1 ha sampling plot with systematic distribution sampling has been conducted in the Tozi reserved forest, Sudan (Yasin and Mulyana, 2022), and Abu Gadaf natural reserved forest in Sudan (Mohammed et al. 2021a). In each plot, the recorded data were the name of the species, number of individuals for each species, diameter at breast height, height using caliper and Haga, and coordinates using GPS.

2.3 Statistical methods

The collected data were processed and analyzed using Microsoft Excel 2016. Important Value Index (IVI) was calculated based on the sum of ecological parameters, namely relative frequency (RF), relative density (RD), and relative dominance (RDo). Frequency is the occurrence of species in the sampling plot. Density represents the total number of individuals of each species in the sampling plot. Dominance is the total basal area for each species in the sampling plot. Relative Abundance (RA) represents the species abundance in the sample plot (Yasin and Mulyana, 2022) – *Table 1*. We used descriptive statistics, similar means, maximum, minimum, percentages, tables, and charts. Using diversity directories, the RF, RD, RDO, IVI, Shannon–Wiener diversity index, Margalef's index (Species Richness), Species Evenness index (E_H), Simpson's Species Diversity index, Index of Dominance of tree species were computed (Ogwu et al., 2016) – *Table 1*. The tree species were classified according to their relative densities (RD) to represent their conservation status. The categories are as follows: abundant (RD ≥ 5.00), Frequent (4.00 ≤ RD ≥ 4.99), occasional (3.00 ≤ RD ≥ 3.99), rare (1.00 ≤ RD ≥ 2.99), and threatened (0.00 < RD ≥ 1.00) (Ogwu et al., 2016).

Table 1. ***The equations used to calculate tree basal area, relative frequency, dominance, and abundance, importance value index (IVI), Simpson's Species Diversity index (D), Margalef species richness index, Shannon-Weiner diversity index (H), and Species Evenness Index of the tree species measured in the AGRFR.***

Equation	Reference
Tree basal area (cm) = $\frac{\pi * (DBH)^2}{4}$	(Mohammed et al., 2021a)
Frequency (F) = Presence or absence of the species per site	(Mohammed et al., 2021b)
Relative frequency (RF) = $\left(\frac{Tree\ species\ frequency}{Total\ frequency\ for\ all\ species}\right) * 100$	(Idrissa et al., 2018)
Dominance (D) = Total basal area of the species	(Ibrahim et al., 2015)
Relative dominance (RD) = $\left(\frac{Species\ dominance}{Total\ dominance\ for\ all\ species}\right) * 100$	(Ibrahim and Osman, 2014)
Abundance (A) = Number of trees per area measured	(Maua et al., 2020)

Relative abundance (RA) = $\left(\frac{Tree\ species\ abundance}{Total\ abundance\ for\ all\ species}\right) * 100$	(Mohammed et al. 2021c)
IVI = Relative frequency + Relative dominance + Relative abundance	(Mohammed, 2019)
Simpson's Species Diversity index (D) = $(\frac{\Sigma n(n-1)}{N(N-1)})$, then 1-D.	(Frerebeau, 2019)
Margalef species richness index (M) = $\frac{(s-1)}{InN}$	(Gamito, 2010)
Species Evenness Index; EH = H / Hmax = $\sum_{i=1}^{s} \frac{piln(pi)}{In(S)}$	(Okpiliya, 2012)
Shannon-Weiner diversity index (H') = - $\Sigma^{s}_{i=1} P_i \ln P_i$	(Shannon and Weaver,1949)

* DBH is a tree diameter measured 1.3 m from the ground and called diameter at breast height (DBH), and IVI is the importance value index.

3 RESULTS

3.1 Tree species diversity trend in the AGRFR during 2011 to 2021

A total of 462 individual trees belonging to 32 species from 15 different families were counted in 2021. The highest species numbers were recorded in the Fabaceae family (10 species), followed by the Moraceae and Meliaceae families, each with (three species). The Fabaceae family had the highest number of individual trees, totaling 146, followed by the Meliaceae with 78 and the Myrtaceae with 74 (*Tables 2 and 3)*.

However, the 2011 inventory of the AGRFR showed 626 individual trees or shrubs, belonging to 23 species from 12 families, as recorded in *Tables 1 and 2*. *Acacia nilotica* had the highest relative density, accounting for 39.94 % in 2011 and 31.6 % in 2021 (*Tables 4 and 5*). The Fabaceae family had the highest species diversity in the ecosystem, with 10 species in 2021 and six species in 2011. The Meliaceae and Moraceae families had three species in both inventory years. Among the 23 species identified in 2011, 21 were classified as trees and two as shrubs. In 2021, 32 species were identified, with 28 classified as trees and six as shrubs (*Tables 2 and 5*).

Table 2. Tree and shrub species type and presence in AGRFR in 2011 and 2021

Family	Species	2011	2021	Local name	Type
Anacardiaceae	*Mangifra indica* L.	✓	✓	Manga	Tree
	Anacardium occidentale L.		✓	Cashew-Nut tree	Tree
Arecaceae	*Elaeis guineensis* Jacq		✓	Oil palm	Tree
	Phoenix dactylifera L.	✓	✓	Nakheel At Tamr	Tree
Balanitaceae	*Balanites aegyptiaca* (Linn.) Del	✓	✓	Helglig, Lalob	Tree
Bombacaceae	*Adansonia digitata* L.	✓	✓	Tabaldi	Tree
Capparaceae	*Boscia senegalensis* (pers.) Lam. Ex poir		✓	Mokhait	Shrub
	Capparis decidua (Forsk) Edgew		✓	Tundub	Shrub
Combretaceae	*Conocarpus lancifolius* Engl. & Diels	✓	✓	Damas	Tree
Fabaceae	*Acacia. nilotica sub sp. tomentosa* (Benth) Brerian	✓	✓	Sunt	Tree
	Acacia siebriana DC.	✓		Kuk	Tree
	Acacia seyal Delile.	✓		Talh	Tree
	Dalbergia sisso DC		✓	Sisso	Shrub
	Fadherbia albida (Del.) A. chev	✓	✓	Haraz	Tree
	Cassia fistula L.		✓	El khoreim	Tree

	*Albizia lebbeck (*L.) Benth		✓	Dign Al Pasha	Tree
	Acacia ehrenbergiana Hayne	✓	✓	Salam	Tree
	Acacia polycantha Willed		✓	Kakamut	Tree
	Dalbergia melanoxylon Guill. & perr		✓	Babanous	Tree
	Delonix regia (Boj.ex Hook.) Raf	✓	✓	Gold moar	Tree
	*Peltophorum petrocarpum (*Dc.) Bacher ex K. Heyne	✓	✓	Peltophorum	Tree
	Khaya senegalensis (Desr.) A. juss	✓	✓	Mahogany	Tree
	Azadirachta indica A. Juss	✓	✓	Neem	Tree
Meliaceae	*Khaya grandifoliola* C. DC	✓	✓	Mahogany	Tree
	Milicia excels (Welw.) C.C. Berg	✓	✓	Abu Hajar	Tree
Moraceae	*Ficus microcarpa* L. F	✓	✓	Ficus	Tree
	Ficus sycomorus L.	✓	✓	Gumaiz	Tree
	Eucalyptus camaldulensis Dehn	✓	✓	Kafoor kamal	Tree
Myrtaceae	*Eucalyptus microtheca* F.Muell	✓	✓	Ban	Tree
Ramnaceae	*Ziziphus spina christi (*Linn.) Desf	✓	✓	Sidr	Shrub
Rutaceae	*Aegle marmelos* corr		✓	elephant apple	Tree
Santalaceae	*Santalum album* L.		✓	Sandal	Shrub
Simaroubaceae	*Ailanthus excels* Roxb	✓	✓	Ailanthus/Alkabriet	Tree
Verbenaceae	*Tectonia grandis* L.F	✓	✓	Teak	Tree

Table 3. Number of genera, number of species and relative frequency (RF) of genus and species within identified families

Family	2011				2021			
	No. genera	No. species	Genus RF (%)	Species RF (%)	No. genera	No. species	Genus RF (%)	Species RF (%)
Anacardiaceae	1	1	5.56	3.7	2	2	7.69	5.88
Arecaceae	1	1	5.56	3.7	2	2	7.69	5.88
Balanitaceae	1	1	5.56	3.7	1	1	3.85	2.94
Bombacaceae	1	1	5.56	3.7	1	1	3.85	2.94
Capparaceae	0	0	0	0	2	2	7.69	5.88
Combretaceae	1	1	5.56	3.7	1	1	3.85	2.94
Fabaceae	3	6	22.2	33.33	7	10	26.9	35.29
Meliaceae	2	3	11.1	11.11	2	3	7.69	8.82
Moraceae	2	3	11.1	11.11	2	3	7.69	8.82
Myrtaceae	1	3	5.56	11.11	1	2	3.85	5.88
Ramnaceae	1	1	5.56	3.7	1	1	3.85	2.94
Rutaceae	0	0	0	0	1	1	3.85	2.94
Santalaceae	0	0	5.56	3.7	1	1	3.85	2.94
Simaroubaceae	1	1	5.56	3.7	1	1	3.85	2.94
Verbenaceae	1	1	5.56	3.7	1	1	3.85	2.94
	16	23			26	32		

3.2 The AGRFR forest structure

Based on the 2021 inventory, the recorded base diameters ranged from a minimum of 6.1 cm to a maximum of 115 cm, with an average of 17.04 cm and a standard deviation (SD) of 11.43 cm. The average total height was 8.94 m, with a standard deviation of 8.07 m. The total heights ranged from a minimum of 5 m to a maximum of 23 m (*Table 4*).

In contrast, the 2011 inventory data revealed that the DBH values varied between 3 cm and 107 cm, with an average of 16.86 cm and a standard deviation of 10.46 cm. The mean total height for this year was 14 m, with a standard deviation of 5.62 m, and the heights ranged from a minimum of 7 m to a maximum of 32 m. The changes in tree diameter and height between the 2011 and 2021 inventories are likely due to a combination of selective logging, environmental changes, forest management practices, natural disturbances, and the age structure of the forest. These factors collectively influence the growth patterns and overall forest structure (Asner et al., 2005).

Table 4. Summary statistics of growing variables in AGRFR

Variables	2021		2011	
	DBH (cm)	Height (m)	DBH (cm)	Height (m)
Maximum	115	23	107	32
Minimum	6.1	5	3	7
Mean	17.04	8.94	16.85	14.29
SD	11.43	8.07	10.46	5.62
Total No. of Individuals	*462*	*277*	*626*	*57*

We found that the distribution of tree diameters at breast height (DBH) ranged from less than 10 cm to more than 60 cm in 2011 (*Figure 2*). The DBH class of 10 cm to 19 cm contained the highest percentage of individual trees, totaling 44.71%, making it the most common category in the area. The DBH class of less than 10 cm included 25.54% of trees. The least represented categories were those with diameters of 50 cm to 59 cm and more than 60 cm, with 1.32% and 0.30% of individual trees, respectively.

Similarly, the 2021 inventory results indicated that the DBH distribution ranged from less than 10 cm to more than 60 cm, with 43% of individual trees falling within the 10 cm to 19 cm DBH class, making it the most common category again. The lowest percentage of individual trees, 0.56% in each category, were found in the diameter classes of 50 cm to 59 cm and more than 60 cm, respectively.

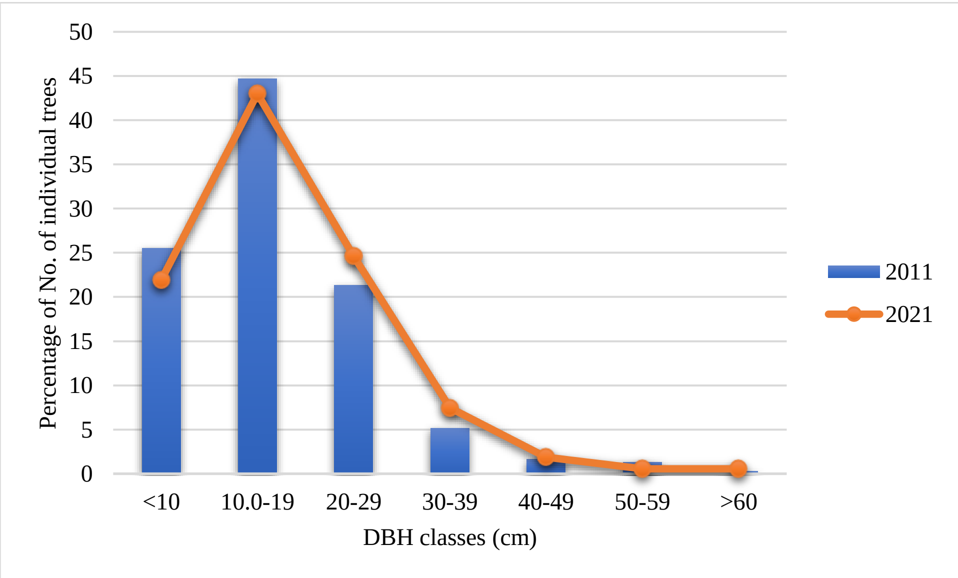

Figure 2. DBH classes distribution of individual tree species count in AGRFR

The results illustrated in *Figure 3* show that the total height of tree species in the study area ranged from less than 10 to 39 meters, according to the 2011 inventory. Moreover, 22.81 % of individual trees were found in the height classes of 15–19 meters and 20–24 meters. This was followed by height classes of less than 10 meters and 10–14 meters, each with 17.55 % of individual trees. The least common height class, 35–39 meters, contained only 1.75 % of individual trees. According to the 2021 inventory, 41.23 % of individual trees were recorded in the height class of 10–14 meters, making it the most common height range in the study area. This was followed by 32.23 % of individual trees in the height class of less than 10 meters and 4.74 % of individual trees in the 20–24 meter height class.

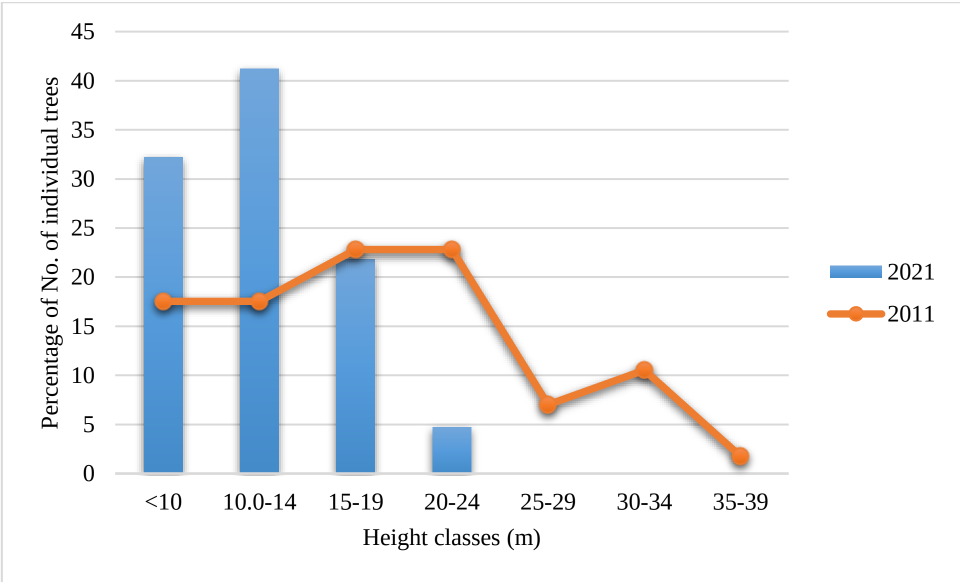

Figure 3. Height classes distribution of individual tree species count in the AGRFR

3.3 Mean basal area, density, and Importance Value Index (IVI) of tree species in the AGRFR

The 2021 inventory results, as shown in *Table 5*, indicate that the basal area for all tree species in the study area ranged from 0.018 to 8.50 m^2/ha, with an overall average basal area of 2.41 m^2/ha. *Khaya senegalensis*, which belongs to the family Meliaceae, had the highest basal area of 8.50 m^2/ha, followed by *Acacia nilotica* at 3.98 m^2/ha and *Faidherbia albida* at 1.90 m^2/ha. *Santalum album* recorded the lowest basal area at 0.018 m^2/ha.

Based on the 2011 inventory, *Acacia nilotica* was identified as the species with the highest density per hectare, with 146.54 trees in 2021 and 390.88 in 2011 in AGRFR (*Table 5).* On the other hand, species like *Ficus sycomorus*, *Mangifera indica*, *Phoenix dactylifera*, *Santalum album*, *Boscia senegalensis*, *Capparis decidua*, *Anacardium occidentale*, and *Aegle marmelos* had the lowest density, at 10 per hectare. The basal area varied from 0.064 to 14.92 m^2/ha, with an average basal area of 3.42 m^2/ha. *Azadirachta indica* had the highest basal area at 14.92 m^2/ha, followed by *Khaya senegalensis* at 14.59 m^2/ha and *Acacia nilotica* at 8.29 m^2/ha. *Ziziphus spina-christi* had the lowest basal area at 0.064 m^2/ha (*Table 5*).

The Importance Value Index (IVI) in both the 2011 and 2021 inventories shows that *Acacia nilotica* had the highest IVI of 63.46 and 47.97, followed by *Khaya senegalensis* with an IVI 33.77 and 36.55, and *Eucalyptus camaldulensis with an IVI 53.98 and 32.55,* respectively. It was followed by *Azadirachta indica* with an IVI of 31.82 and *Ailanthus excelsa* with 25.83 in 2011. *Khaya grandifoliola* had an IVI of 15.76 in the 2021. *Ziziphus spina-christi* and *Santalum album* had the least dominant values of 1.43 and 1.20 in 2011 and 2021, respectively. The IVI also highlights *Acacia nilotica* as the most dominant tree species, with an IVI value above 47 (*Table 5*).

Table 5. Tree Species density, basal area, and Importance Value Index in the AGRFR in 2011 and 2021

Species	Inventory 2011				Inventory 2021			
	No. of individual tree	Mean density No. ha^{-1}	Mean BA (m^2 ha^{-1})	IVI	No. of individual tree	Mean density No. ha^{-1}	Mean BA (m^2 ha^{-1})	IVI
Acacia nilotica	250	390.88	8.29	63.46	146	146.54	4.00	47.97
Acacia siebriana	2	20	4.49	8.42	0	0	0	0
Acacia seyal	4	40	1.17	6.89	0	0	0	0
Acacia ehrenbergiana	1	10	1.39	3.11	3	30	0	0
Acacia polycantha	0	0	0	0	2	20	0.76	2.94
Adansonia digitata	2	10	2.40	4.40	2	20	7.69	11.91
Aegle marmelos	0	0	0	0	1	10	0.35	1.42
Ailanthus excels	62	124	7.12	25.83	20	28.57	1.06	7.88
Albizia lebbeck	0	0	0	0	2	20	3.96	7.08
Anacardium occidentale	0	0	0	0	1	10	0.20	1.24
Azadirachta indica	19	95	14.92	31.82	21	52.5	1.26	10.19
Balanites aegyptiaca	4	20	1.24	4.28	6	20	0.45	3.40
*Boscia senegalensis*r	0	0	0	0	1	10	0.86	2.08
Capparis decidua	0	0	0	0	2	10	0	0
Cassia fistula	0	0	0	0	16	80	1.93	12.06
Conocarpus lancifolius	6	20	1.02	4.00	4	20	1.51	4.34
Dalbergia sisso	0	0	0	0	48	240	4.29	34.27
Dalbergia melanoxylon	0	0	0	0	4	40	0.62	4.71
Delonix regia	5	16.66	0.38	2.73	6	20	0.69	3.72
Elaeis guineensis	0	0	0	0	2	20	3.47	6.44
Eucalyptus microtheca	6	20	1.23	4.27	8	26.6	2.56	7.07
Eucalyptus camaldulensis	189	378	2.21	53.98	66	165	4.37	32.55
Fadherbia albida	4	20	2.58	5.98	23	46	3.80	13.41
Ficus microcarpa	3	15	0.34	2.46	4	20	0.83	3.46
Ficus sycomorus	3	30	0.60	4.82	2	10	0.80	2.23
Khaya grandifoliola	4	40	6.08	13.14	4	40	9.16	15.76
Khaya senegalensis	45	112.5	14.59	33.77	53	88.3	14.17	36.55
Mangifra indica	3	30	4.64	9.96	1	10	2.83	4.63
Milicia excels	4	20	2.90	6.39	3	15	3.18	5.91
Peltophorum petrocarpum	2	20	0.45	3.28	2	20	0.83	3.03
Phoenix dactylifera	2	10	0.42	1.88	1	10	0.71	1.89
Santalum album	0	0	0	0	1	10	0.18	1.2
Tectonia grandis	5	25	0.16	3.58	3	30	0.53	3.62
Ziziphus spina Christi	1	10	0.06	1.43	4	20	0.27	2.73
Total	626		78.67		462		77.31	

3.4 Trend in species conservation status between 2011 and 2021

Based on the inventories conducted in 2011 and 2021, the relative tree species density (RD) ranged from 0.16 % to 39.94 % and 0.216 % to 31.6 %, respectively. *Acacia nilotica*, which belongs to the family Fabaceae, recorded the highest densities of 39.94 % and 31.6 % each year, respectively. In the 2011 inventory, *Ziziphus spina Christi* and *Acacia ehrenbergiana* had the lowest density at 0.16 %. In the 2021 inventory, the lowest density at 0.22 % was noted for

Anacardium occidentale, Boscia senegalensis, Mangifera indica, Phoenix dactylifera, and *Santalum album*. The Shannon-Weiner diversity index (H') for 2021 and 2011 was calculated at 2.39 and 1.75, respectively. These results also indicated that *Acacia nilotica* species were categorized as abundant. Most tree species were classified as threatened, with a few categorized as rare, occasional, or frequent (*Table 6*).

Table 6. Temporal changes in tree species diversity, relative density, and conservation status in 2011 and 2021

	2011			2021		
Tree species	Diversity index (H')	RD	Classification Based on RD	Diversity index (H')	RD	Classification Based on RD
Acacia nilotica	0.37	39.94	Abundant	0.01	31.60	Abundant
Acacia siebriana	0.02	0.32	Threatened	0.00	0.00	-
Acacia seyal	0.03	0.64	Threatened	0.00	0.00	-
Acacia ehrenbergiana	0.01	0.16	Threatened	0.02	0.65	Threatened
Acacia polycantha	0.00	0.00	-	0.06	0.43	Threatened
Adansonia digitata	0.02	0.32	Threatened	0.01	0.43	Threatened
Aegle marmelos	0.00	0.00	-	0.02	0.22	Threatened
Ailanthus excels	0.23	9.90	Abundant	0.36	4.32	Frequent
Albizia lebbeck	0.00	0.00	-	0.24	0.43	Threatened
Anacardium occidentale	0.00	0.00	-	0.15	0.22	Threatened
Azadirachta indica	0.11	3.04	Occasional	0.12	4.54	Frequent
Balanites aegyptiaca	0.03	0.64	Threatened	0.02	1.30	Rare
*Boscia senegalensis*r	0.00	0.00	-	0.03	0.22	Threatened
Capparis decidua	0.00	0.00	-	0.25	0.43	Threatened
Cassia fistula	0.00	0.00	-	0.14	3.46	Occasional.
Conocarpus lancifolius	0.05	0.96	Threatened	0.28	0.87	Threatened
Dalbergia melanoxylon	0.00	0.00	-	0.14	0.87	Threatened
Dalbergia sisso	0.00	0.00	-	0.02	10.39	Abundant
Delonix regia	0.04	0.80	Threatened	0.02	1.29	Rare
Elaeis guineensis	0.00	0.00	-	0.01	0.43	Threatened
Eucalyptus microtheca	0.05	0.96	Threatened	0.01	1.73	Rare
Eucalyptus camaldulensis	0.36	30.19	Abundant	0.03	14.29	Abundant
Fadherbia albida	0.03	0.64	Threatened	0.04	4.97	Frequent
Ficus microcarpa	0.03	0.48	Threatened	0.04	0.87	Threatened
Ficus sycomorus	0.03	0.48	Threatened	0.06	0.43	Threatened
Khaya grandifoliola	0.03	0.64	Threatened	0.07	0.87	Threatened
Khaya senegalensis	0.19	7.19	Abundant	0.04	11.47	Abundant
Mangifra indica	0.03	0.48	Threatened	0.02	0.22	Threatened
Milicia excels	0.03	0.64	Threatened	0.04	0.65	Threatened
Peltophorum petrocarpum	0.02	0.32	Threatened	0.02	0.43	Threatened
Phoenix dactylifera	0.02	0.32	Threatened	0.01	0.22	Threatened
Santalum album	0.00	0.00	-	0.01	0.22	Threatened
Tectonia grandis	0.04	0.80	Threatened	0.03	0.65	Threatened
Ziziphus spina Christi	0.01	0.16	Threatened	0.04	0.87	Threatened

The data in *Table 7* illustrate the growth variables and diversity indices for various tree families, genera, and species based on inventories taken in 2011 and 2021. The 2011 inventory recorded 12 families, 16 genera, 23 species, and 626 individual trees, with a total basal area of 78.67 m^2. In contrast, the 2021 documentation showed an increase in the number of families, genera, and species to 15, 26, and 32, respectively. However, the number of individual trees decreased to 462, with a total basal area of 77.31 m^2. The results from inventories taken in 2011 and 2021 indicate variations in species abundance and threat status. In 2011, 17.39 % of species were classified as abundant, which decreased to 12.5 % by 2021. Conversely, threatened species constituted a substantial majority, with 78.26 % in 2011 and 65.63 % in 2021. Occasional species accounted for 4.35 % in 2011 and declined slightly to 3.13 % in 2021. Furthermore, the 2021 inventory also identified 9.38 % of species as frequent and rare (*Table 7*).

The Shannon-Wiener diversity index (H) recorded values of 1.75 in 2011 and 2.39 in 2021, indicating an increase in species diversity. The Margalef index, which measures species richness, showed values of 93.64 in 2011 and 70.8 in 2021 for the forest ecosystem. Species evenness also improved, from 0.56 in 2011 to 0.69 in 2021. Furthermore, Simpson's diversity index, which assesses the diversity of a community by considering the number of species and the abundance of each species, 0.73 in 2011 increased to 0.84 in 2021 (*Table 7*).

Table 7. Summary of stand structural variables and diversity indices in the AGRFR in 2011 and 2021

Growth variables and diversity indices	Inventory year 2011	Inventory year 2021
Number of families	12	15
Genera	16	26
Number of tree species	23	32
Density (Tree ha^{-1})	208.67	154
Number of trees	626	462
Total basal area (m^2 ha^{-1})	78.67	77.31
Basal area (m^2 ha^{-1})	3.42	2.41
Abundant (Relative density; RD ≥ 5)	4 (17.39%)	4 (12.50%)
Frequent (4.00 ≤ RD ≥ 4.99)		3 (9.38%)
Occasional (3.00 ≤ RD ≥ 3.99)	1 (4.35%)	1 (3.13%)
Rare (1.00 ≤ RD ≥ 2.99)		3 (9.38%)
Threatened/ Endangered (0.00 < RD ≤ 1)	18 (78.26%	21 (65.63%)
Shannon–Wiener (Diversity index (H)	1.75	2.39
Margalef's index (Species Richness)	93.64	70.8
Species Evenness index (E_H)	0.56	0.69
Simpson's Species Diversity index	0.73	0.85
Index of Dominance	14.58	5.71

4 DISCUSSION

4.1 Trends of structural variables of the AGRFR

The AGRFR has minimum and maximum diameters at breast height (DBH) of trees recorded at 6.1 cm and 115 cm, respectively. This reserve is noted for its abundance of trees with smaller DBH, a common feature of tropical forests. This observation aligns with findings from previous studies in other tropical rainforests of Nigeria, as reported by Adekunle and Olagoke (2008), Adekunle et al. (2013), Akindele (2013) and Aigbe et al. (2014). The relatively lower number of trees with larger DBH values, exceeding 50 cm, is primarily due to selective logging practices, including removing large trees through logging for various uses in the past, as noted by Hadi et al. (2009). According to Adekunle et al. (2013), the distribution of diameter and height reflects the forest's horizontal structure and vertical patterns, indicating the forest's potential for continuous growth. Furthermore, the presence of large trees is often considered a sign of a mature tropical rainforest.

4.2 Trends of species somposition, diversity, and IVI

The 32 tree species from 15 different families documented in the Abu Geili River Forest Reserve (AGRFR) underscore the area's considerable diversity, a hallmark of robust ecosystems, as noted by Okey et al. (2022) and Mohamed et al. (2021). Among these, the Fabaceae, Moraceae, and Meliaceae families were most prevalent. Although the count of individual tree species diminished in 2021 compared to 2011, the diversity of species and families increased in the same period.

In contrast, studies in other regions have reported varying levels of diversity. For instance, Dafa-Alla et al. (2022) found just 14 species, representing a significantly lower diversity in Jebel Elgarri forest, Blue Nile state, Sudan. Similarly, minimal diversity was recorded in Sinnar state, Sudan's Tozi tropical dry forest, with only four species across two families reported by Yasin and Mulyana (2022). Conversely, Mohammed et al. (2021a) observed greater diversity in the Abu Gadaf natural reserve, Sudan, with 47 species from 20 families. A much richer biodiversity was noted in the Ehor forest reserve, Edo State, southern Nigeria by Ihenyen et al. (2009), who identified 99 species from 87 genera and 36 families. Ecological zones and anthropogenic activities such as logging and deforestation particularly affect the AGRFR (Yeom and Kim, 2011; Liu et al., 2024) and significantly influence the variability in species.

The prevalence of the Fabaceae, Meliaceae, and Moraceae families, known for their resilience and rapid regeneration, mirrors findings from other studies in Nigerian forest reserves by Mukhtar (2002), Edet et al. (2012) and Aigbe et al. (2014) in Sudanese tropical forests. These characteristics likely help these families dominate in varied environments despite the threats from human activity.

Ecological indices further highlight these dynamics. The Shannon-Wiener diversity index values increased from 1.75 in 2011 to 2.39 in 2021, suggesting an improvement in biodiversity within the reserve. This index value surpasses the 1.928 noted by Dafa-Alla et al. (2022) in Sudan but is below the higher values reported in rainforests in India and Nigeria by Pragasan and Parthasarathy (2010), Adekunle and Olagoke (2008), respectively. This positive trend may reflect natural regeneration, reduced disturbances, and successful conservation efforts.

Despite the overall growth in the index, its comparatively low value may reflect ongoing natural and human pressures, underscoring the need for enhanced governance and regulatory reforms to protect and enhance the forest's biodiversity.

The importance value index (IVI) further elucidates species dominance within the reserve. *Acacia nilotica* topped the 2011 inventory with an IVI of 80.7, while the 2021 survey showed a decrease, with *Khaya grandifoliola* following at an IVI of 46.3. The lowest IVIs were recorded for *Santalum album* and *Ziziphus spina-christi*, likely impacted by their commercial and medicinal value, leading to higher logging rates. This indicates the economic implications of tree species removal, emphasizing the necessity for targeted conservation efforts for both dominant and lesser-represented species (Abdullahi, 2021; Wilfahrt et al., 2023).

4.3 Trend in species conservation status between 2011 and 2021

The inventories conducted in 2011 and 2021 revealed significant changes in the relative density (RD) and conservation status of tree species within the Abu Geili Riverine Forest Reserve (AGRFR). *Acacia nilotica* consistently recorded the highest densities, though its RD decreased from 39.94 % in 2011 to 31.6 % in 2021, indicating a slight decline in its dominance. Meanwhile, *Ziziphus spina christi* and *Acacia ehrenbergiana* had the lowest density at 0.16 % in 2011. By 2021, the lowest density of 0.216 % was shared by *Anacardium occidentale*, *Boscia senegalensis*, *Mangifera indica*, *Phoenix dactylifera*, and *Santalum album*, showing an increase in the diversity of species with very low densities.

The Shannon-Weiner diversity index (H') increased from 1.75 in 2011 to 2.39 in 2021, indicating a significant improvement in species diversity. This increase suggests that the forest ecosystem has become more balanced, with a greater variety of species contributing to its overall composition. Despite this improvement in diversity, most tree species were still classified as threatened in both years. However, the data shows some progress: in 2011, 78.26 % of species were considered threatened, which decreased to 65.63 % in 2021. This decline reflects positive changes in the conservation status of several species, likely due to effective management and conservation efforts.

Overall, while the forest has seen improvements in species diversity and a decline in the percentage of threatened species, challenges remain. The decrease in *Acacia nilotica's* relative density, along with the still high proportion of threatened species, underscores the need for ongoing conservation efforts, highlighting the importance of continued monitoring and adaptive management strategies to enhance the forest's health and ensure the long-term sustainability of its diverse species.

5 CONCLUSIONS

The comparative analysis of the AGRFR across the years 2011 and 2021 reveals substantial shifts in the forest's diversity and tree composition. The 2021 inventory counted 462 trees across 32 species and 15 families, whereas less than 626 trees were identified in 2011. The Fabaceae family had the highest number of species recorded (10 species), followed by Moraceae and Meliaceae families, each with (three species), emphasizing the ecological diversity within the forest. Despite shifts in tree density and diversity measures, the forest still shows resilience and a rich ecological environment. In particular, *Acacia nilotica* demonstrated its ecological significance through its abundance and high Importance Value Index (IVI). The most common trees were found in the height range of 10 to 14 meters and a DBH class of 20 to 29 cm. With smaller trees, DBH of 17 cm and below was also dominant.

Nevertheless, the decline in tree numbers and changes in species richness and evenness point to the impacts of environmental stress and human activities, highlighting the urgent need for conservation initiatives to ensure forest sustainability. Despite this, the AGRFR exhibited low tree species density alongside high species diversity. Urgent conservation measures are required to mitigate the risk of species extinction and address the adverse effects of logging and other illegal activities on the forest's structure and diversity. Protecting the AGRFR from anthropogenic impacts is essential to prevent further deforestation and degradation, ensuring the long-term preservation of its unique species and ecological balance.

Acknowledgements: The author extends heartfelt gratitude to the Faculty of Natural Resources and Environmental Studies, University of Sinnar, Sudan, for their invaluable support of this research. Additionally, appreciation is due to Forest National Corporation offices at Sinnar state for offering the required information.

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