

Synthesizing knowledge about tree diversity, density, and distribution in the savanna woodlands of Sudan

Ahmed M.M. Hasoba^{a,b,*}, Ahmed A.H. Siddig^{c,d}, Kornel Czimmer^a, Ali Omer^{c,e}, Nasradeen A.H. Gadallah^{c,f}, Mohamed M.A. Adam^{c,g}, Audrey Barker Plotkin^d

^a Faculty of Forestry, University of Sopron, Bajcsy-Zsilinszky ut. 4, Sopron, 9400, Hungary

^b Faculty of Forest Sciences and Technology, University of Gezira, Wad Madani P. O. Box 20, Sudan

^c Faculty of Forestry, University of Khartoum, Khartoum North, Postal Code 13314, Sudan

^d Harvard Forest, Harvard University, 324N. Main St, Petersham, MA 01366, USA

^e Division of BioInvasions, Global Change & Macroecology, Department of Botany and Biodiversity Research, University of Vienna, Rennweg 14, Vienna 1030, Austria

^f African Centre of Excellence on Climate Change, Biodiversity and Sustainable Agriculture, University Felix Houphouët-Boigny, Abidjan, Côte d'Ivoire

^g Department of Plant Production, College of Food and Agriculture Sciences, King Saud University, Saudi Arabia

ARTICLE INFO

Keywords:

Acacia seyal, Conservation status
Ecosystem management
Species occurrence
Tree diversity

ABSTRACT

Savanna ecosystems comprise a complex and diverse biome, marked by the balanced cohabitation of trees and shrubs alongside a rich assembly of herbaceous flora, particularly grasses. In Sudan, savanna ecosystems provide invaluable services that sustain the livelihoods of millions of people. Here, we synthesized the existing knowledge about tree density, diversity, and distribution in the savanna woodlands of Sudan to assess tree diversity, evaluate tree conservation status on the basis of tree abundance and distribution according to IUCN guidelines, and map tree diversity and density in savanna woodlands. The research process started with an extensive search for relevant literature across various databases. The data sources included Google Scholar and Web of Science, as well as reports and publications available in the libraries of Sudanese universities. The results revealed that savanna woodland contains 163 tree species belonging to 40 families. Fabaceae was the most frequent family, accounting for 44 species. The species richness among the sites ranged from 1 to 73 species, and the stand density ranged from 20.5 to 500 stems/ha. Moreover, this study revealed that *Acacia seyal*, *Acacia senegal*, *Balanites aegyptiaca*, and *Ziziphus spina-christi* are the most frequent species and that these four key species are well distributed throughout the savanna woodland of Sudan. While this first synthesis of tree diversity and distribution lacked data at the sample plot level, it should stimulate further research in this crucial ecosystem.

Introduction

Savanna ecosystems comprise a diverse and complex biome that is characterized by the coexistence of woody vegetation (trees and shrubs) and herbaceous flora (grasses). Trees are the dominant woody species of the savanna ecosystem, influencing its overall structure and composition (Rozendaal and Chazdon, 2015). Since trees accumulate more biomass than shrubs and herbaceous species do, they drive nutrient cycles and carbon sequestration. In contrast to grasses and forbs, trees provide essential habitats for many species. In addition, savanna trees affect microclimates by reducing wind impact and providing shade, which subsequently affect the distribution and quantity of other plants and animal life (Niinemets and Valladares, 2004). Savannas cover 40 %

(15.1 million km²) of the global terrestrial area and approximately 45 % of the land surface in Sub-Saharan Africa (Mishra and Crews, 2014; Gwenzi, 2017; Warth et al., 2020). Savannas play a significant role in local and global ecological functions, such as carbon sequestration, with great variation in vegetation structure, following the differences in climatic, topographic, edaphic, and biological factors (Gwenzi, 2016; Axelsson, 2018).

The savanna zone in Sudan is a significant source of ecosystem goods and services that support the livelihoods of millions of people in the country (Hasoba et al., 2020). Moreover, savanna vegetation provides habitat for biodiversity, enhances soil fertility, and protects the environment against erosion and desertification. However, the savanna zone is in continuous decline due to both severe anthropogenic interventions

* Corresponding author.

E-mail addresses: Hasoba.Ahmed@phd.uni-sopron.hu, Ahmedhasoba899@gmail.com (A.M.M. Hasoba).

<https://doi.org/10.1016/j.tfp.2025.100906>

(e.g., deforestation, land use change, and grazing) and climate change, resulting in profound deterioration in savanna vital biodiversity and ecosystem services (Millennium Ecosystem Assessment, 2005; Western et al., 2009; Woinarski et al., 2010; Romero-Ruiz et al., 2012; IPBES, 2019; Shukla et al., 2019; Yasin and Mulyana, 2022). Knowledge about the current composition, abundance, and structure of forest stands, as highlighted by Su et al. (2010), is essential for understanding changes within savanna ecosystems. Additionally, this knowledge offers valuable insights into how ecosystems have responded to past environmental disturbances and threats, facilitating the forecasting of future trends in species richness and turnover, as emphasized by Young et al. (2017), and Hido et al. (2020). Hence, studies focusing on tree species inventories and diversity are fundamental to understanding and managing the floristic composition and diversity status of these areas. These investigations not only provide essential information for savanna conservation, as noted by Yakubu et al. (2020) but also contribute significantly to the effective management of forest resources (Teketay 2005; Mishra et al., 2013). Furthermore, owing to its strong correlation with other biodiversity attributes, such as genetic diversity and ecosystem functioning (Colwell and Coddington, 1994; Pereira and Cooper, 2006; Chiarucci and Palmer, 2009) and efficiency of application (Cherice et al., 2012) species diversity is the most commonly used indicator in studies describing the biodiversity of forest ecosystems (Barna and Bosela, 2015; Schmidt et al., 2015; Shirima et al., 2015; Vanderhaegen et al., 2015).

Unfortunately, the relative abundance, density, and diversity of trees in this important ecological zone are not well documented. In particular, in Sudan, most studies on vegetation diversity are fragmented, very local and focused only on the forest stand level (Siddig, 2019). Thus, the

available literature on tree density, diversity, and occurrence is sparse and inconsistent (Hasoba et al., 2020; Dafa-alla et al., 2022; Gadallah et al., 2022; Hassan et al., 2022; Mohammed et al., 2022; Yasin and Mulyana, 2022). For example, different studies have reported varying estimates of stand characteristics, such as relative density, for the same species (e.g., *Acacia seyal*) in the same stand or woodland. This is not only confusing but also leads practitioners to erroneous decisions (Siddig, 2019). Upscaling estimates of stand characteristics for some important savanna trees, such as *Acacia* sp., from collated data from multiple local forests can provide managers with better information and improve planning for conservation interventions and utilization throughout the entire savanna zone. Therefore, there is an urgent need to synthesize the current state of knowledge of savanna woodlands in Sudan.

This study aims to quantitatively synthesize the literature to improve the knowledge of tree diversity, density, and distribution in the savanna woodlands of Sudan. This study used data from 21 study sites with specific objectives of synthesizing available information on tree diversity and density and mapping their distribution in the savanna woodland of Sudan.

Study area and methods

The extent of savanna in Sudan

Sudan is classified into five distinct climatic zones characterized by vegetation composition, rainfall patterns, and soil types. These zones span from the desert in the northern regions to the verdant savanna in the southern part of the country, along with other ecological zones and

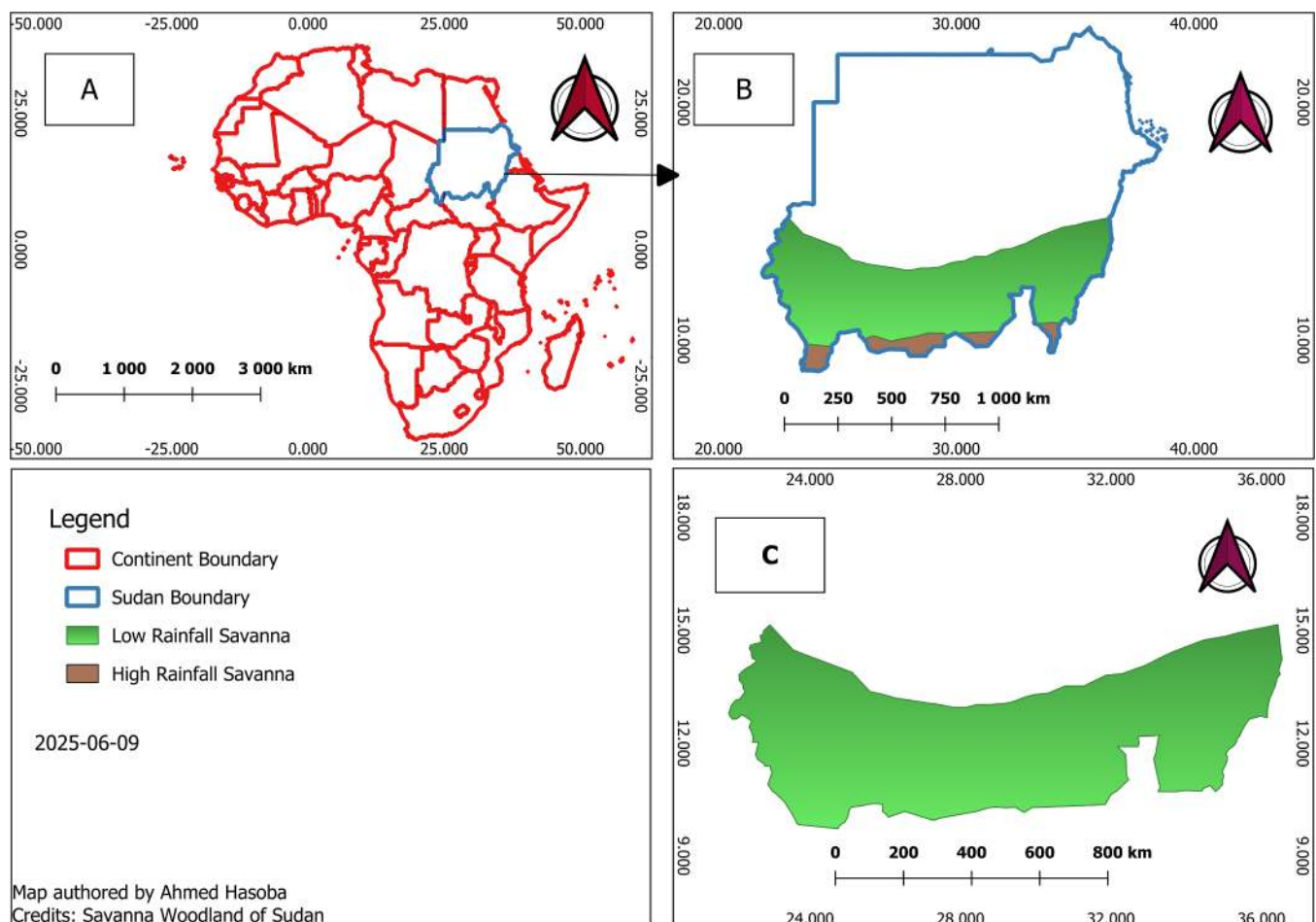


Fig. 1. Location of the Savanna Woodland in Sudan. (A) African continent, (B) Sudan Boundary, and (C) savanna woodland.

special regions such as semidesert, flood riverine, and montane vegetation area (Harrison and Jackson, 1958). This study was conducted in savanna woodland located in southern Sudan. This ecosystem covers 553,470 km² and lies between 9. 80° - 15.20° 'N and 36. 20° - 22. 20° 'E (Fig. 1). The woodland savanna is a type of vegetation that consists of grass, shrubs and trees that grow in areas with annual rainfall ranging from 250 to over 1000 mm (Harrison and Jackson, 1958). The amount of rainfall and the soil quality affect the diversity of plants in this vegetation. There are two subtypes of woodland savanna: a) low rainfall savanna and b) high rainfall savannah. The high rainfall savanna is found only in some parts of southern Darfur, such as southern Dafoug and southern Talodi, where the Nuba belt is located. The low rainfall savanna covers the rest of the woodland savanna areas. The line that separates the two subtypes is between the isohyets 800–1000 mm (Abdel-Magid and Badi, 2005).

The vegetation cover of savannas consists of mostly thorny plants with thick bark that can withstand fire. The clayey soil in the dry north supports low *Acacia mellifera* shrubs. The southern border is defined by places such as Gedarif, Renk and Gelhak in the Upper Nile. More rain (570 mm per year) leads to taller *Acacia seyal* and *Balanites* trees that grow in Gedarif, the Blue Nile (Siddig, 2019; Abuelbasher et al., 2022) southern Kordofan (Ismail and Elawad, 2015; Bokhary and El awad 2016) and the upper Nile. They mix with *Acacia senegal* near hills or rocks in southeastern Gedarif (Ismail, 2021) the Blue Nile and the Upper Nile, and the plants are *Anogeissus* and *Combretum hartmannianum*. These plants shift to high-rainfall savannas with taller, thinner, and wider-leaved trees. The northern parts of North Kordofan and North Darfur (Hegazy et al., 2021; Ekhlas et al., 2022) are covered by the *Acacia senegal* savanna, which stretches toward Nuhud to el Fasher. This ecoregion comprises two types of soil, mainly clay and sandy soil (Abdel-Magid and Badi, 2005).

Nevertheless, the savanna of Sudan suffer from several human activities such as grazing (Bokhary and El awad 2016; Ismail, 2020a, 2021; Mohammed et al., 2021; Abuelbasher et al., 2022; Ekhlas et al., 2022) tree-cutting (Ismail, 2021) and cutting down trees for crop production are some of these activities (Ismail, 2020b). In several locations, grazing is widespread, which causes soil compaction and vegetation deterioration. The removal of trees, mostly for building and fuel wood, has an impact on species composition and tree density at several locations. Furthermore, there is extensive land clearance for agricultural expansion, with a large amount of land being turned into crop fields, which lowers the amount of forest cover overall. The way that the ecosystems of savanna woodlands are currently shaped is greatly influenced by these activities.

Research methodology

The research process began with an extensive search for relevant literature via Google Scholar and Web of Science, as well as governmental reports and publications available in the libraries of Sudanese universities. Using a systematic literature review, we compiled a comprehensive dataset through a search strategy that incorporated a combination of keywords, including "Sudan savanna woodlands," "tree density," "tree diversity," and "tree distribution." The search was limited to articles, reports, dissertations or thesis chapters published between 2015 and 2023.

In this study, we applied strict inclusion and exclusion criteria to ensure the selection of high-quality, relevant studies for our synthesis. We included only peer-reviewed articles, books, or reports, including those published in Sudanese journals that provided quantitative data on tree density, species diversity (e.g., richness), and distribution within Sudan's savanna woodlands. Studies lacking such data or classified as gray literature (e.g., unpublished reports) were excluded due to concerns about methodological rigor. The screening process involved reviewing titles and abstracts, followed by a full-text assessment to verify data quality and relevance. Whereas some study sites correspond

to the same geographic location, they represent independent studies conducted by different authors at different times. These studies employed distinct methodologies, sampling strategies, and reported varying ecological metrics, such as species richness, tree density, and regeneration indices. Including these studies enriches the dataset by capturing diverse perspectives on the ecological dynamics of these sites. While the majority of included studies met all predefined criteria, study no 17 (Table 1) was retained despite lacking data on stand density due to its valuable contribution to tree species composition and diversity metrics. This exception was made to ensure comprehensive coverage of species-level patterns in Sudan's savanna woodlands and is noted here for transparency. We also note that the studies included in this analysis applied a variety of approaches for data collection. Plot shapes varied among studies, with researchers utilizing circular, rectangular, and square plots. The sampling strategies also differed, encompassing both random and systematic approaches, with line, strip, and zigzag patterns being employed. Despite this variation in sampling design, shape and methods, all studies used a consistent sample area of 1000 m². Importantly, the minimum diameter at breast height (DBH) used to define a tree varies, ranging from a DBH ≥ 5 cm to a DBH ≥ 10 cm. For detailed methodological characteristics, consult (Table 1).

Data analysis

Out of the 54 assessed articles, only 21 articles and datasets were found to be eligible for calculating tree density and species richness for savanna woodland ecosystems after the application of the strict inclusion criteria. By collating a list of individual tree species from these diverse locations, a unified list of tree species composition within the savanna ecosystem of Sudan was constructed.

To assess tree diversity, for each family, we calculated the total number of species observed in savanna woodlands of Sudan with respect to the study sites. Then, for each tree species in our dataset, we calculated the absolute frequency of occurrence on the basis of its presence across the 21 datasets. Moreover, the relative frequency of each tree species was calculated via the following equation: Relative frequency (%) = (number of specific species present/total number of sites) × 100. Finally, we used species relative frequencies to assign each species into one of the following five classes: 1) rare (< 5 %) refers to species occurring at minimal frequencies; 2) low (5–25 %) refers to species with moderate but not pervasive presence; 3) common (25–50 %) refers to species exhibiting a prevalent but not dominating occurrence; 4) abundant (50–80 %) refers to species with substantial prevalence and a notable presence; and 5) superabundant (> 80 %) refers to species demonstrating an overwhelmingly frequent presence within savanna woodlands. To calculate the average density, each forest or study area was treated as an individual sample point ($n = 20$), then an arithmetic mean was calculated across these sites. After that, we calculated the standard error based on the following equation $SE = \text{Standard Deviation} / \text{square root of sample size}$.

In this study, the spatial distribution and geographical context of the study sites within the Sudanese savanna were analyzed via Geographic Information Systems (GIS) software, specifically the Quantum Geographic Information System (QGIS). A map representing the geographical locations of the 21 selected forests was generated, providing an overview of the study's spatial coverage across the savanna region. This map serves as a valuable spatial reference, illustrating the distribution of the investigated and sampled sites within the broader savanna zone.

Furthermore, to examine the spatial distribution of key tree species within the savannas of Sudan, each individual forest or study area was treated as an individual sample point (a total of 21 samples). The analysis focused on assessing the occurrence of four significant tree species, namely, *Acacia seyal*, *Acacia senegal*, *Balanites aegyptiaca*, and *Ziziphus spina-christi*, across these sampled areas. Leveraging geographical coordinates in terms of longitude and latitude, distributional maps

Table 1
Description of the 21 study sites.

No	Forest Name	Location / state	Area (ha)	Number of plots	Sample Area	Sample Shape	DBH Limits	No. Species	Density trees/ha	Source
1	Jebel El Gerrie Natural Forest	Blue Nile	5040	97	1000 m2	Circular	DBH $\geq$ 10 cm	15	47	Dafa-alla et al., 2022
2	Abu Gadafe Natural Forest	Blue Nile	4413.87	46	1000 m2	Rectangular	DBH $\geq$ 7 cm	47	55	Mohammed et al., 2021
3	Jebel Elgarrie Natural Forest	Blue Nile	5805.1	90	1000 m2	Circular	DBH $\geq$ 10 cm	15	46	Abuelbasher et al., 2022
4	Remila Riverine Forest	Sinnar	NA	11	1000 m2	Rectangular	DBH $\geq$ 7 cm	1	157	Hassan et al., 2022
5	Badous Riverine Forest	Blue Nile	76.98	10	1000 m2	Rectangular	DBH $\geq$ 7 cm	13	356	Hassan et al., 2022
6	Fazara Natural Forest	Gedarif	7095.76	74	1000 m2	Rectangular	DBH $\geq$ 7 cm	13	184	Hassan et al., 2022
7	Abu Gadaf Natural Forest Reserve	Blue Nile	4413.87	46	1000 m2	Rectangular	DBH $\geq$ 7 cm	46	257	Hassan et al., 2022
8	Okalma Natural Forest	Sinnar	17,639.5	178	1000 m2	Rectangular	DBH $\geq$ 7 cm	10	219	Hassan et al., 2022
9	Wad Ayies Natural Forest	Sinnar	7160.86	75	1000 m2	Rectangular	DBH $\geq$ 7 cm	8	219	Hassan et al., 2022
10	Nuara Reserved Forest	Sinnar	2560	638	1000 m2	Circular	DBH $\geq$ 5 cm	4	191	Hasoba et al. 2020
11	Jebel Algerri Natural Forest	Blue Nile	NA	40	1000 m2	Circular sample	NA	44	183	Ismail and ElSheikh, 2016
12	El-Salam Locality	West Kordofan	1093,000	136	NA	Point centered quarter	NA	25	20.5	Tutu et al., 2019
13	Umabdalla Natural Forest	South Kordofan	4396.55	Na	1000 m2	Circular	DBH $\geq$ 10 cm	53	60	Abdelkareem et al., 2020
14	Tozi Natural Forest	Sinnar	6031.2	306	1000 m2	Circular	DBH $\geq$ 7 cm	4	175	Yasin and Mulyana, 2022
15	Rashad District	South Kordofan	787,200	8	400 m2	Square	NA	56	NA	Eisawi et al., 2021
16	Alfula District	West Kordofan	974,679	40	1000 m2	Circular	Na	58	330	Ismail, 2020b
17	Jebel Mara	Central Darfur	900,000	52	100 m2	Na	Na	62	NA	Hegazy et al., 2021
18	Jebel El-Dair	North Kordofan	31,445	23	1000 m2	Circular	Na	47	500	Ismail, 2020a
19	Al Galabat District	Gedarif	NA	36	1000 m2	Circular	Na	37	324	Ismail, 2021
20	Zalingei District	Central Darfur	244,756.7	60	1000 m2	Circular	Na	33	428	Khlyfa et al., 2022
21	El Ain Natural Forest	North Kordofan	18,695	927	1000 m2	Circular	Na	73	104.25	Bokhary and Elawad, 2016

were constructed. The spatial interpolation for the tree species was conducted via the radial basis function (i.e., gridding method) in surfer 9 (Golden Software LLC, 2009). This interpolation approach facilitated better visualization of species occurrence patterns, enabling the prediction of their spatial extent in areas without presence-absence data and providing insights into their habitat preferences and distributional range. We used the same method to create a distribution map for forest stand density and tree species diversity (Fig. 2).

Results

Tree species diversity and density in savanna woodlands of sudan

Our synthesis revealed marked spatial variability in tree species richness across Sudan's savanna woodlands. Elain Reserved Forest (North Kordofan) exhibited the highest richness, with 73 recorded species. This diversity is likely attributed to its designation as a pilot site for various intentional management initiatives, which brought enhanced protection measures. In contrast, the Remila Riverine Forest (Al Gedarif) recorded only a single species, primarily due to its management objectives by the Forest National Corporation, which focus on timber production from *Acacia nilotica*. This stark contrast highlights how land-use goals, management intensity, and ecological heterogeneity central themes in our research framework shape tree diversity across the region (Table 1 and Fig. 6).

Our synthesis identified 163 tree species belonging to 40 families

within Sudan's savanna woodlands. Fabaceae was the most frequent family, represented by 44 species (27 %), reflecting its ecological prominence in African savannas due to nitrogen-fixation capacity and drought tolerance (Tindano et al., 2015). Combretaceae and Malvaceae followed, each with 12 species, while Capparaceae, Anacardiaceae, and Rubiaceae contributed 11, 9, and 8 species, respectively. Notably, 19 families (47.5 %) were represented by only one species, revealing a long-tailed diversity structure in which rare taxa may be particularly vulnerable to habitat fragmentation and local extinction (Fig. 3).

The 21 sites exhibited a diverse range of dominant tree species, with *Acacia seyal* being the most frequently dominant species prevailing at sites 2, 6, 7, 9, 10, and 14, followed by *Acacia nilotica* (sites 4 and 5), *Anogeissus leiocarpa* (sites 1 and 3) and *Combretum hartmannianum* (sites 1 and 11). Other dominant species included *Acacia senegal* at site 8, *Balanites aegyptiaca* at site 12, *Adansonia digitata* at site 15, *Geuara senegalensis* at site 16, *Boscia senegalensis* at site 18, *Boswellia papyrifera* at site 19, *Albizia amara* at site 20, and *Acacia mellifera* at site 21. Three sites (12, 13, and 17) lacked a clear dominant species.

In this study, the average tree density is 208 trees per hectare (SE = 30.8) across Sudan's savanna woodlands, with pronounced spatial variability that reflects the influence of ecological and anthropogenic drivers. The highest recorded density observed was 500 trees/ha in the Jebel El-Dair Natural Reserve (North Kordofan) likely due to its protected status and mesic microclimate, which reduce the impact of anthropogenic disturbances typically observed in unprotected areas. In contrast, El-Salam Locality (West Kordofan) exhibited the lowest

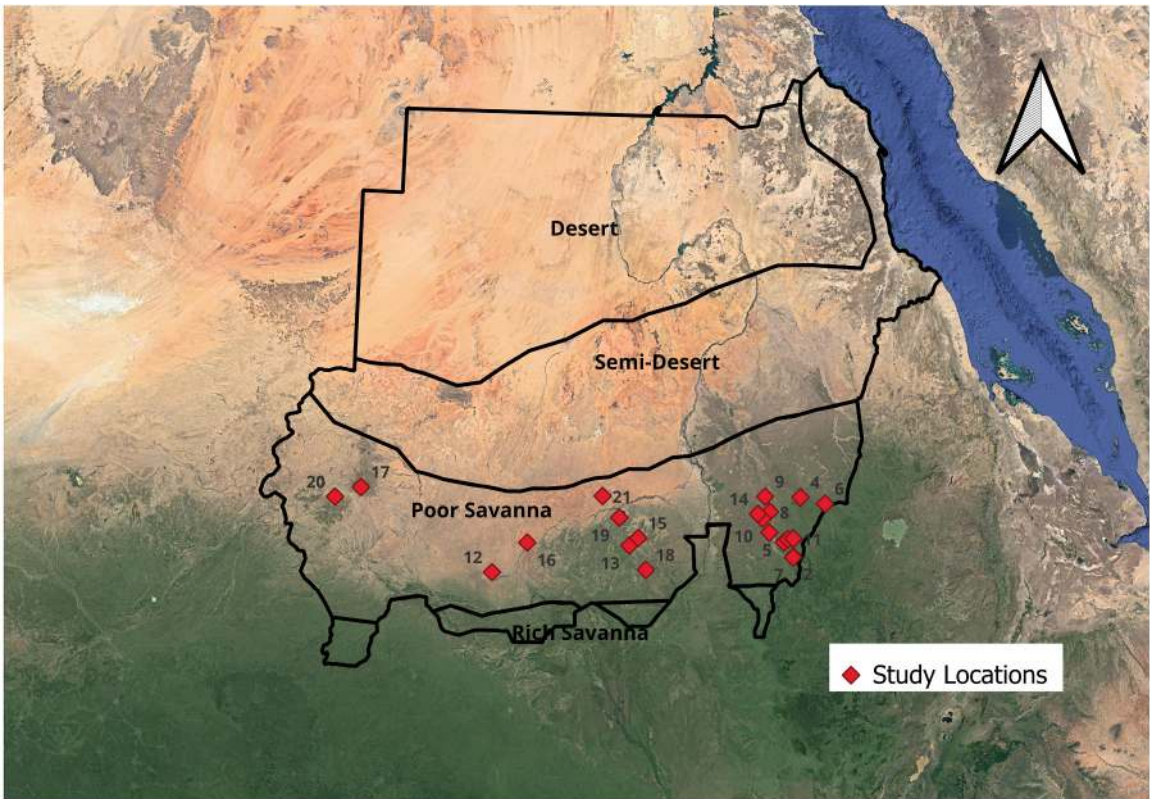


Fig. 2. Map of Sudan, showing the distribution of the 21 study sites within the poor savanna region (site numbers match those found in Table 1).

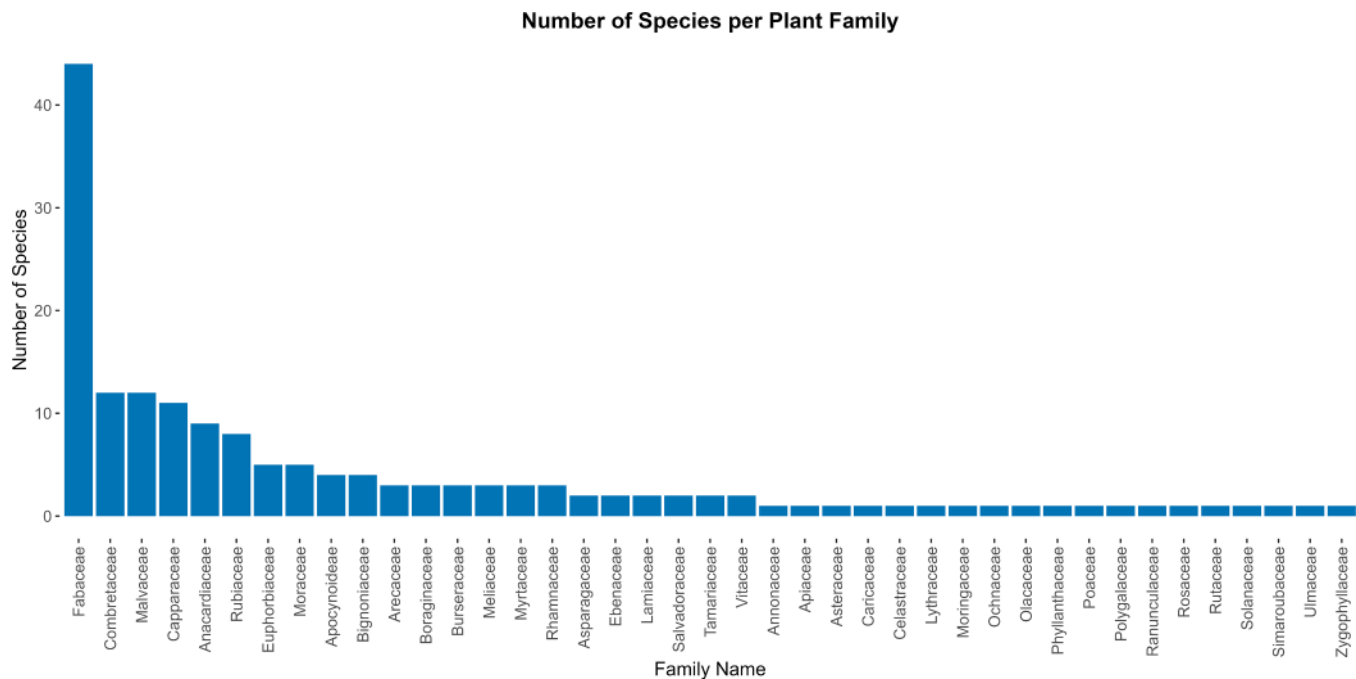


Fig. 3. Number of tree species in each family.

density, with only 20.5 trees/ha, a figure that aligns with the effects of human-induced pressures such as grazing, logging, and land conversion (Table 1 and Fig. 6).

Conservation status of tree species

On the basis of the 21 studies compiled in this paper, four species were classified as super abundant (2 % of all species), six species were classified as abundant (4 %), 28 species were classified as common (17 %), 51 species belonged to the low-abundance class (31 %), and 74

species were classified as rare species (45 %) (Fig. 4). The detailed classification for each species is provided in appendix A.

Spatial distribution of four key species, tree diversity and stand density

Fig. 5 highlights the distribution patterns of four superabundant species across the savanna landscape, offering critical insights into their spatial dynamics within the Sudanese savanna ecosystem. Both *Acacia seyal* and *Acacia senegal* have relatively large distribution ranges compared with the other two species. However, the center of their distribution is spatially separated, whereas *Acacia seyal* centers in the areas where *Acacia senegal* trees are absent, whereas *Acacia senegal* trees are more likely to be found in the western part of the savanna woodlands where *Acacia seyal* trees are absent. On the other hand, *Balanites aegyptiaca* and *Ziziphus spina-christi* have relatively small distribution ranges and seem to share the same niche (Fig. 5).

The distribution map of forest stand density demonstrated significant spatial variation across the savanna woodland of Sudan (Fig. 6). High-density areas, with densities reaching up to 500 stems/ha, are concentrated in the southern and western regions. These areas encompass a natural reserve mountain park, which, owing to its relatively undisturbed conditions and limited access caused by high elevation, appears to be more resilient to anthropogenic pressures. Conversely, the south-eastern savanna shows markedly lower densities, with some areas exhibiting densities as low as 20.5 stems/ha. Two additional low-density sites were found in the central region, where human activities such as grazing and logging likely contributed to the reduction in tree cover.

The distribution of tree species across savanna woodlands revealed distinct spatial patterns (Fig. 6). The highest levels of species diversity were recorded in the western (73 species) and central (62 species) regions. In contrast, low-diversity areas were concentrated in the eastern region, with sites containing as few as 1–10 species.

Discussion

The present study revealed that tree species richness ranged from 1 to 73 species per site, with a total of 163 species recorded across all savannas. This number is lower than that reported for South American savanna (Françoso et al., 2016) with 907 species from 167 studies; some

of these differences are likely due to the greater number of studies included in the South American synthesis. On the other hand, the number of 163 species reported here is greater than the number of 91 species reported in Senegal (Sylla et al., 2025). Among the 21 sites in this study, the highest absolute richness value (73 species) was observed in the Elian Natural Forest, which is located in the near-central part of Sudan. This number is lower than that reported in other areas, such as South America (Françoso et al., 2016; Ter Steege et al., 2023), with 158 and 357 species, respectively, in other floristic surveys (Batalha and Martins, 2007; Ratter et al., 2003). However, 73 species are more common than those reported for savanna woodlands of southern Africa (40 species at the richest site (Sebungwe)) and northern Guinea-Savanna (53 species) (Mutowo and Murwira, 2012; Sobola et al., 2021). The relatively high species richness in Elian may be attributed to the presence of heterogeneous ecological features, including mountain ranges, natural forest patches, and water reserves, which are known to support greater biodiversity (Bokhary and Elawad, 2016).

Differences in richness and diversity throughout the savanna woodlands of Sudan are likely due to both deforestation through the clearance for agriculture and degradation through the consumption of woodland products and natural and anthropological disturbances (Gadallah et al., 2021). Agriculture provides both income and nutrition for local people, and the consumption of woodland products is equally important to their livelihoods, as savanna woodland provides a wide range of ecosystem services and goods such as edible fruits, firewood, and building material for local communities (hassan et al., 2022).

At the family level, Fabaceae, Combretaceae, Malvaceae, Capparaceae, Anacardiaceae, and Rubiaceae were the most frequent families in the savanna woodlands of Sudan, collectively accounting for over 58 % of the plant community across all studies synthesized in this review. This observation is consistent with findings from the forest-savanna ecotone of Ghana (Attua and Pabi, 2013) and the savanna vegetation of Senegal (Sylla et al., 2025), where similar patterns of family-level dominance have been reported. The predominance of Fabaceae aligns with observations from other tropical and semi-arid ecosystems, where this family frequently dominates due to its nitrogen-fixing capabilities, which enhance soil fertility and support ecosystem productivity even under nutrient-poor conditions (Tindano et al., 2015). Similarly, Combretaceae species are well adapted to dry environments and are known

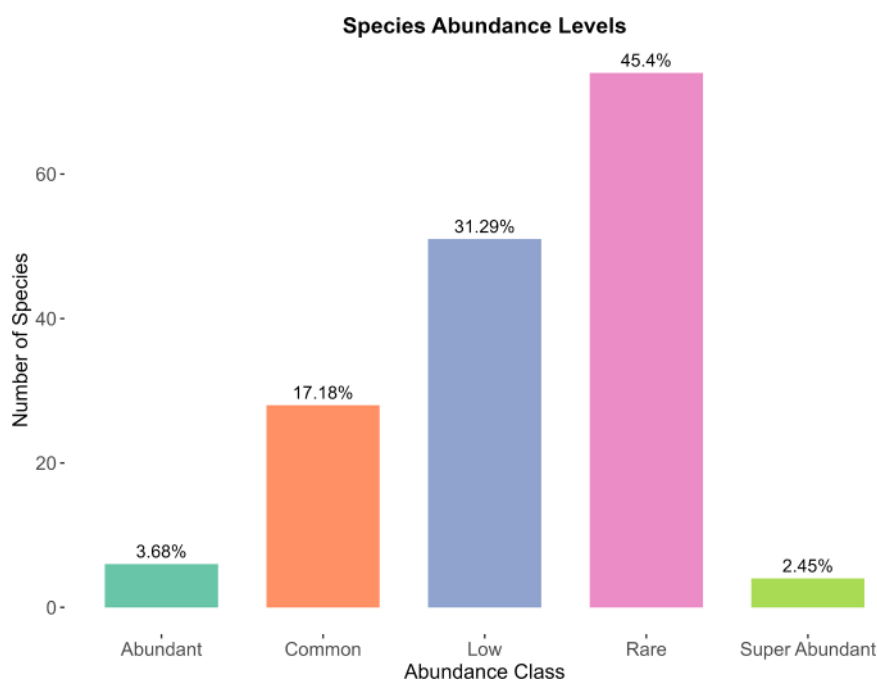


Fig. 4. Distribution of species across different abundance levels in the studied savanna woodlands.

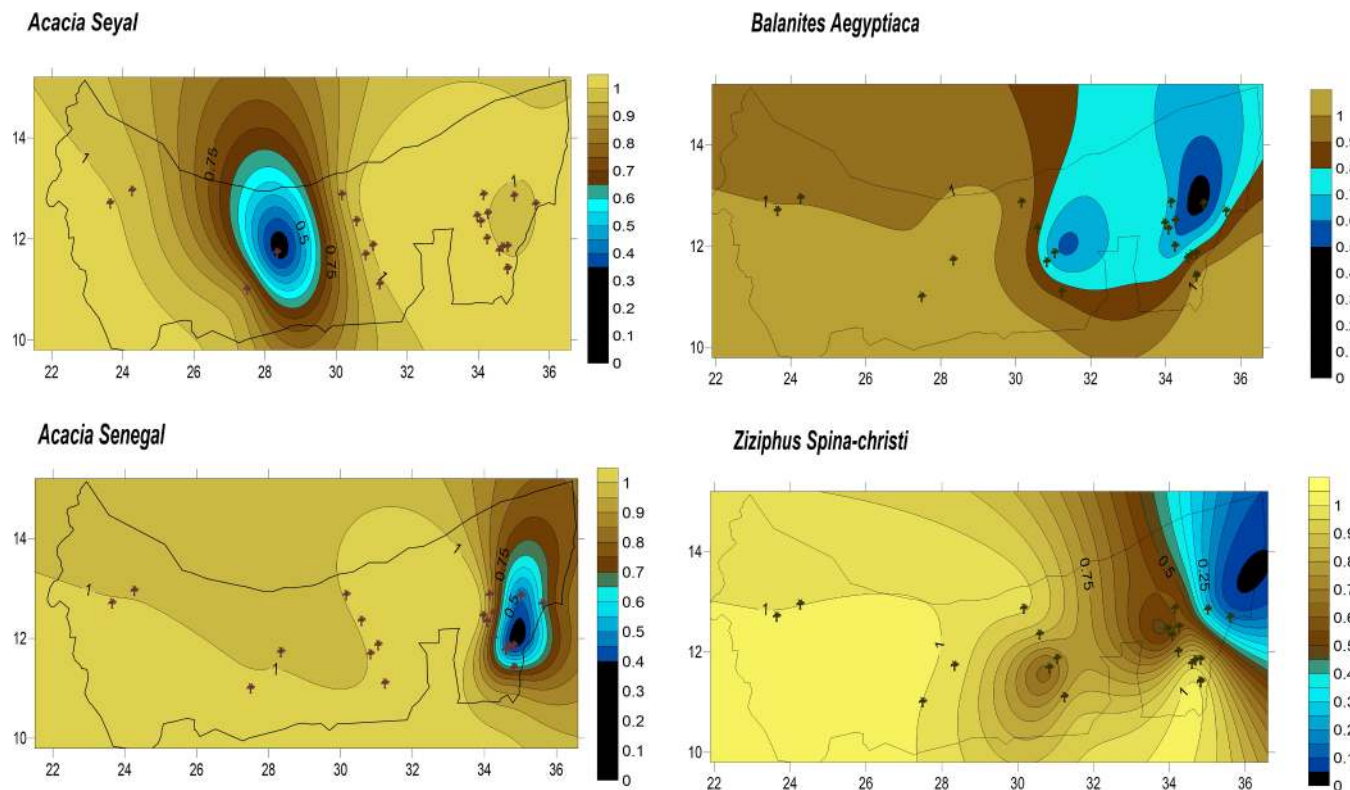


Fig. 5. Distribution of *Acacia seyal*, *Acacia senegal*, *Balanites aegyptiaca*, and *Ziziphus spina-christi* in Savanna Woodland, on the basis of their presence and absence in the 21 studies synthesized in this study. The scale (0–1) represents the likelihood of species presence, where 0 indicates absence and 1 indicates high presence.

for their drought tolerance, enabling them to thrive in savanna habitats characterized by seasonal water scarcity (Tindano et al., 2014). The dominance of these families suggests a significant influence on the structure and composition of Sudan's savanna woodlands. Their adaptive traits to local environmental stressors, coupled with their ecological functions such as nitrogen fixation, climate regulation, and provisioning of food and shelter for local wildlife highlight their essential roles in maintaining the resilience and functioning of these ecosystems.

The 21 studies synthesized here show that stand density varies from 20.5 tree/ha to 500 tree/ha. This value is lower than that reported in other studies conducted in the Sudanian savanna biome, such as in Burkina Faso, where Nikiema (2005) observed a stand density of 1967 trees/ha, and (Sobola et al., 2021) reported 600–737 trees/ha in northern Guinea-Savanna. However, the density estimates reported in this study were higher than the 127 ± 15 to 164 ± 12 stems/ha reported in the northern forest-savanna ecotone of Ghana (Attua and Pabi, 2013). The highest recorded tree density, reaching 500 trees per hectare, was observed in the Jebel El-Dair Natural Reserve. This area, though legally protected, experiences limited enforcement. We attribute this exceptionally high stand density to the mountainous nature of the terrain. The rugged topography likely provides natural protection for tree growth by limiting accessibility and thereby reducing the frequency and intensity of anthropogenic disturbances, as noted by Gebeyehu et al. (2019) and Hammond et al. (2021). In contrast, the lowest tree density, recorded at 21 trees per hectare, was observed in El-Salam Locality. This low density is likely a consequence of severe anthropogenic disturbances, which have significantly degraded the forest structure in these areas. We suggest that the broad range of tree density observed among these studies and regions is due to human management intensity, as stated by (Schroth and Harvey, 2007). These findings underscore the critical role of conservation management and localized ecological conditions in shaping forest structure insights that are essential for guiding sustainable forest policy in Sudan's vulnerable savanna regions.

The spatial analysis revealed distinct distribution patterns among the

four key tree species across the 21 sampled forests. *Acacia seyal* and *Acacia senegal* showed broader distributions across savanna woodland, while *Balanites aegyptiaca* and *Ziziphus spina-christi* were more spatially restricted, indicating narrower ecological niches or greater sensitivity to environmental variation. These patterns reflect species-specific habitat preferences. *Acacia seyal* and *Balanites aegyptiaca* were common in low-elevation, clay-rich soils of the central and eastern savanna, supporting previous findings of their co-occurrence (El Mahi and Magid, 2014). *Acacia senegal* was more dominant in well-drained, sandy soils in the drier western zones, consistent with (Magid et al., 2014). Interpolation results revealed that areas of high stand density often coincided with higher species richness, especially in central regions like Elian Natural Forest. These areas likely benefit from reduced disturbance and greater habitat heterogeneity. In contrast, the eastern savanna showed lower diversity and density, likely due to grazing, land use pressure, and arid conditions (Mohammed et al., 2021). The radial basis function (RBF) interpolation method used in Surfer 9 effectively visualized species distribution patterns from limited field data. While useful for predicting spatial trends, it may not fully capture abrupt changes caused by localized disturbances (Hao et al., 2022). These findings highlight priority areas for conservation and restoration. Regions with high richness and density should be protected, while degraded zones offer opportunities for targeted ecological recovery and sustainable management planning.

Finally, the studies included in this analysis presented some methodological heterogeneity that may have affected our findings. Plot shapes varied, with some studies utilizing circular plots considered most efficient for capturing spatial distribution, whereas others employed rectangular or square plots, which may be less effective for unevenly distributed trees, a typical savanna tree distribution. The sampling strategies also differed, encompassing both random and systematic approaches. Random sampling is generally preferred to avoid spatial bias, but some studies might have employed systematic approaches due to logistical constraints. Line, strip, and zigzag transect patterns further

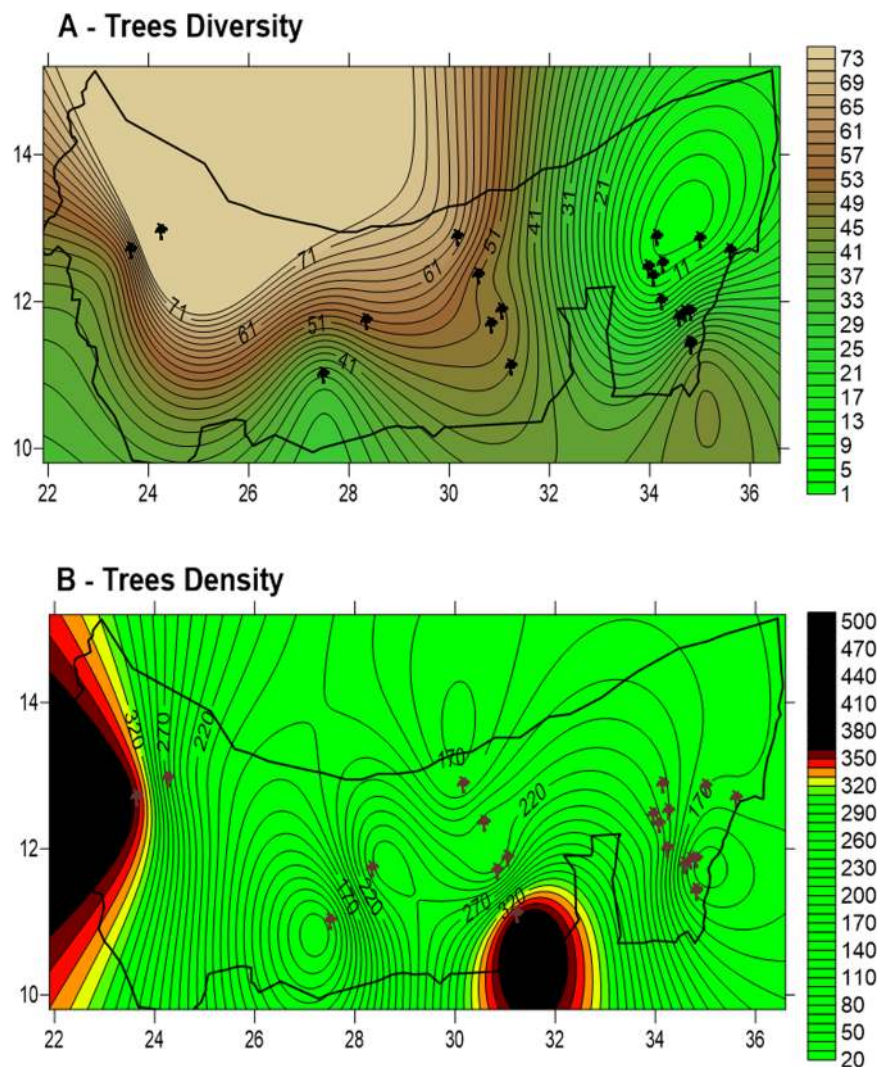


Fig. 6. Distribution maps of tree diversity and stand density in the Sudanese savanna. A illustrates the spatial distribution of tree diversity, ranging from 1 to 73 species per location, whereas B shows the distribution of stand density, ranging from 20 to 500 trees per hectare. The color gradients represent varying levels of diversity and density.

introduced variation, potentially affecting the detection of clumped tree distributions. Furthermore, the minimum diameter at breast height (DBH) used to define a tree varies considerably across studies, ranging from $\text{DBH} \geq 5$ cm to $\text{DB} \geq 10$ cm. This inconsistency can significantly influence the number of tree species captured, particularly smaller individuals and shrubs. Consequently, directly comparing species composition, richness, and abundance across studies becomes challenging because of the potential underestimation or overestimation of certain tree populations depending on the chosen DBH threshold.

Study limitations

Our synthesis has several limitations that should be considered when interpreting the findings. First, methodological inconsistencies across the 21 included studies introduce potential biases. Variations in plot geometry (e.g., circular, rectangular, square) and sampling strategies (e.g., random, systematic, transect-based) complicate direct comparisons of results. Although all studies standardized plot sizes to 1000 m², differences in diameter at breast height (DBH) thresholds ranging from ≥ 5 cm to ≥ 10 cm likely influenced estimates of tree density and species richness. These discrepancies underscore the critical need for standardized data collection protocols in future research to ensure comparability and reliability.

Second, the limited number of eligible studies (21 out of 54) constrains the spatial and ecological representativeness of our findings. Strict inclusion criteria, particularly the requirement for quantitative data on tree density, diversity, and distribution metrics, excluded many studies, potentially biasing the dataset toward more intensively studied regions or ecosystems. This limitation highlights the scarcity of robust, quantitative studies in certain areas of Sudan's savanna woodlands.

Third, the temporal scope of the synthesis (2015–2023) captures recent trends but omits longer-term ecological dynamics. This relatively narrow timeframe limits our ability to generalize findings across Sudan's diverse savanna landscapes, which are shaped by both historical and contemporary environmental and anthropogenic factors. Future studies should aim to incorporate longer-term datasets to provide a more comprehensive understanding of savanna woodland dynamics.

Fourth, A key limitation of this synthesis is the potential impact of clonal growth on estimates of tree density and species abundance. Savanna species like *Combretum spp.*, *Balanites aegyptiaca*, and *Acacia spp.* can regenerate through root suckers or coppicing, especially after disturbances such as fire or grazing (Ouedraogo and Thiombiano, 2012). The reviewed studies often did not distinguish between ramets (clonal stems) and genets (genetically distinct individuals), which may lead to overestimations of individual tree numbers. This could affect interpretations of species dominance and population dynamics. We

recommend that future assessments in Sudanese savanna woodlands use genetic or structural methods to accurately identify clonal propagation, improving diversity and density estimates.

Finally, the substantial variation in study site sizes introduces additional challenges in data interpretation. These differences reflect the heterogeneity of the datasets included in our synthesis and may affect the precision of cross-site comparisons. While we accounted for these variations during analysis, this limitation underscores the importance of aligning study scales and methodologies in future research.

Conclusion

This study revealed high tree diversity within savanna woodlands, identifying 163 species belonging to 40 families. Fabaceae emerged as the frequent family, contributing 27 % (44 species) of the total. Species richness and stand density varied across the 21 surveyed sites, ranging from 1 to 73 species and 20.5 to 500 stems per hectare, respectively. Notably, *Acacia seyal*, *Acacia senegal*, *Balanites aegyptiaca*, and *Ziziphus spina-christi* have emerged as the most prevalent species, potentially reflecting their competitive advantage and resilience under harsh environmental conditions (Eltayb and Magid, 2013; El Mahi and Magid, 2014; Neelo et al., 2015). The spatial distribution analysis further provided valuable insights into species assemblages and ecological gradients, enabling, to some extent, the identification of biodiversity hotspots and areas of ecological vulnerability. These findings offer a practical foundation for targeted conservation and restoration planning. While limitations in data from sample plots hindered further analysis of diversity indices and habitat characterization, this study provides a valuable baseline assessment of the tree community within savanna woodlands.

Recommendations and future directions

Based on the current findings of this study, along with previous calls from other relevant research (e.g., Siddig, 2014, 2019; Hasoba et al., 2020; Gadallah et al., 2025), the following recommendations are proposed::

1. The establishment of a comprehensive long-term monitoring program involves establishing permanent sample plots to gather time series data critical for assessing the ecosystem's status and understanding the dynamics of tree populations and changes within the savanna ecosystem.

2. Establishment of a Centralized Database: Developing a centralized database that consolidates all available information, including ecological data, species inventories, habitat characteristics, and any ongoing or historical research findings, would be immensely beneficial. This database could serve as a repository for all collected data, ensuring accessibility to researchers, policymakers, and conservationists.

3. Standardized Data Collection Protocols: Implementing standardized protocols for data collection across various research efforts ensures uniformity and consistency in the data gathered. This approach enhances the reliability and comparability of information, enabling more robust analyses and facilitating collaboration among different studies.

4. Future Field Studies: incorporate methods to assess clonal growth to improve the accuracy of stand structure and density estimations.

5. Development of Conservation Initiatives: The survey identified 74 species found in only one location. Hence, emphasizing continued conservation initiatives is crucial to safeguarding the diverse species within savanna woodlands. These initiatives should focus on conserving rare and threatened species in this ecosystem.

6. Training and Capacity Building: the human resources required for this work can be developed through specialized training programs in conservation approaches, biodiversity monitoring and analysis.

7. Future Studies: high-priority studies include 1) understanding the impacts of climate change on some savanna trees, such as the distribution of gum-producing trees through species distribution modeling (SDM), and 2) estimating savanna ecosystem services, such as carbon stock, gum production and net primary productivity.

CRediT authorship contribution statement

Ahmed M.M. Hasoba: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ahmed A.H. Siddig:** Writing – review & editing, Validation, Investigation, Conceptualization. **Kornel Czimer:** Writing – review & editing, Visualization, Supervision, Software. **Ali Omer:** Writing – review & editing, Validation. **Nasradeen A.H. Gadallah:** Writing – original draft, Visualization, Formal analysis. **Mohamed M.A. Adam:** Writing – review & editing, Data curation. **Audrey Barker Plotkin:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The first author sincerely acknowledges the Stipendium Hungaricum Scholarship for its generous support. He also extends his heartfelt gratitude to the University of Sopron for providing invaluable academic resources and guidance throughout the course of this study. Their unwavering support has been instrumental in the successful completion of this work.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.tfp.2025.100906](https://doi.org/10.1016/j.tfp.2025.100906).

Data availability

No data was used for the research described in the article.

References

- Abdel Magid, T.D. and Badi, K.H. (2005). Ecological zones of the Sudan. Paper prepared for the Nile Basin initiative in Sudan (biodiversity in Sudan, 2005).
- Abdelkareem, O.E.A., Eltahir, M.E.S., Elamin, H.M.A., Suliman, A.E. (2020). Structure, composition and plant-species diversity in Umabdalla Natural Reserved Forest, South Kordofan–Sudan.
- Abuelbasha, A.I., Ahmed, D.A., Siddig, A.A., Yagoub, Y.E., Gibreel, H.H., 2022. Analysis of composition and diversity of natural regeneration of woody species in Jebel El Gerrie dry land forest east of Blue Nile State, Sudan. *Journal of forest and environmental science* 38 (2), 90–101. <https://doi.org/10.7747/JFES.2022.38.2.90> (2022).
- Attua, E.M., Pabi, O., 2013. Tree species composition, richness and diversity in the northern forest-savanna ecotone of Ghana. *J Appl Biosci* 69, 5437–5448. <https://doi.org/10.4314/jab.v69i0.95069>. Oct 10.
- Axelsson, C.R.A., 2018. Study of African Savanna Vegetation Structure, Patterning, and Change. South Dakota State University. <https://openprairie.sdstate.edu/etd/2639>.
- Barna, M., Bosela, M., Barna, M., Bosela, M., 2015. Tree species diversity change in natural regeneration of a beech forest under different management. *For. Ecol. Manage.* 342, 93–102. <https://doi.org/10.1016/j.foreco.2015.01.017>. Apr 15.
- Batalha M.A., Martins F.R. (2007). The vascular flora of the cerrado in Emas National Park (Central Brazil): a savanna flora summarized. *Brazilian archives of biology and technology.* (2007); 50:269–77. DOI:10.1590/S1516-89132007000200012.
- Bokhary, A., El Awad, A., 2016. Plant biodiversity assessment and its contribution in the livelihood of local communities: a case study of El Ain Reserved Forest, North Kordofan, Sudan. *International Journal of Science and Research (IJSR)* 5 (9), 21–29. <https://doi.org/10.21275/ART20161416>.
- Chiarucci, A., Palmer, M.W., 2009. The inventory and estimation of plant species richness. *Encyclopedia of life support systems (EOLSS)* 94–116.

- Chirici, G., McRoberts, R.E., Winter, S., Bertini, R., Brändli, U.B., Asensio, I.A., Bastrup-Birk, A., Rondeux, J., Barsoum, N., Marchetti, M., 2012. National forest inventory contributions to forest biodiversity monitoring. *Forest Science* 58 (3), 257–268. <https://doi.org/10.5849/forsci.12-003> (2012) Jun 1.
- Colwell, R.K., Coddington, J.A., 1994. Estimating terrestrial biodiversity through extrapolation. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 345 (1311), 101–118. <https://doi.org/10.1098/rstb.1994.0091> (1994) Jul 29.
- Dafa-Alla, D.A., Abuelbasher, A.I., Gibreel, H.H., Yagoub, Y.E., Siddig, A.A., Hasoba, A. M., 2022. Assessing trees diversity in Jebel Elgarrie Forest Reserve in the Blue Nile State, Sudan. *Journal of Forest and Environmental Science* 38 (3). <https://doi.org/10.7747/JFES.2022.38.3.1> (2022) Sep1-000.
- Eisawi, K.A., He, H., Shaheen, T., Yasin, E.H., 2021. Assessment of tree diversity and abundance in rashad natural reserved forest, South Kordofan, Sudan. *Open Journal of Forestry* 11 (01), 37 (2021) Jan 29.
- Ekhlas, A.Kh., Ismail, M.I., Alawia, A.E., 2022. Ecological diversity and floristic composition of woody vegetation through six ecosystems in Zalingei locality. *Neelain Journal of Science and Technology* 5 (July), 56–65 (2022).
- El Mahi, A.G., Magid T.D. (2014). The potential of Acacia seyal as a resourceful tree for Gum Arabic in Sudan. *Gum Arab. Board (Sudan)*. Khartoum.
- Eltayb, M.T., Magid, T.D., 2013. Effect of felling period and types on acacia seyal (Del) ability to generate by sprouts in Rawashda forest. *Gedarif State, Sudan. J. For. Prod. Ind.* 2, 13–20 (2013).
- Françoso, R.D., Haidar, R.F., Machado, R.B., 2016. Tree species of South America central savanna: endemism, marginal areas and the relationship with other biomes. *Acta Bot Brasilica* 30, 78–86. <https://doi.org/10.1590/0102-33062015abb0244> (2016) Jan.
- Gadallah, N., Hano, A., Musa, O., 2021. Evaluation and modelling of disturbances and threats in Wad AlBashir Tropical Dry Forest, Elgadari State, Sudan. *Sudan Journal of Desertification Research* 12 (1) (2021) Jul 12.
- Gadallah, N.A., Taha, I.S., Hano, A.I., Siddig, A.A., Bo, H.J., 2022. Integrated approach for assessment and monitoring of forests conditions in the drylands of Sudan. *Arid Ecosystems* 12 (2), 142–153. <https://doi.org/10.1134/S2079096122020032> (2022) Jun.
- Gadallah, N.A., Gone Bi, Z.B., Ongoma, V., Omer, A., Ahmed, A.E., Hasoba, A.M., Siddig, A., 2025. Investigating tree diversity and structure across varying land cover classes and altitudes in the savanna woodlands of Sudan. *Frontiers in Forests and Global Change* 8, 1581188. <https://doi.org/10.3389/ffgc.2025.1581188>.
- Gebeyehu, G., Soromessa, T., Bekele, T., Teketay, D., 2019. Species composition, stand structure, and regeneration status of tree species in dry fromontane forests of Awi Zone, northwestern Ethiopia. *Ecosyst. Heal. Sustain.* 5, 199–215. <https://doi.org/10.1080/20964129.2019.1664938>.
- Golden Software, LLC, 2009. Surfer 9 (Version 9) [Computer software]. Golden Software, LLC. Available at <https://www.goldensoftware.com>.
- Gwenzi, D., 2017. Lidar remote sensing of savanna biophysical attributes: opportunities, progress, and challenges. *Int J Remote Sens* 38 (1), 235–257. <https://doi.org/10.1080/01431161.2016.1259683> (2017) Jan 2.
- Hammond, M.E., Pokorný, R., Okae-Anti, D., Gyedu, A., Obeng, I.O., 2021. The composition and diversity of natural regeneration of tree species in gaps under different intensities of forest disturbance (2021). *J. For. Res.* <https://doi.org/10.1007/s11676-020-01269-6>.
- Harrison, M.N., Jackson, J.K., 1958. *Ecological Classification of the vegetation of the Sudan*. Sudan Gov. Khartoum HCENR (1958).
- Hasoba, A.M., Siddig, A.A., Yagoub, Y.E., 2020. Exploring tree diversity and stand structure of savanna woodlands in southeastern Sudan. *J Arid Land* 12 (4), 609–617. <https://doi.org/10.12074/202010.00025> (2020) Jul.
- Hassan, T.T., Mohammed, E.M., Magid, T.D., 2022. Exploring the current status of forest stock in the areas bordering Dinder Biosphere Reserve, Sudan. *Journal of Forestry and Natural Resources* 1 (1), 11–25 (2022) Feb 15. <https://journals.hu.edu.et/hu-journals/index.php/jfmr/article/view/174>.
- Hao, G., Guo, J., Zhang, W., Chen, Y., Yuen, D.A., 2022. High-precision chaotic radial basis function neural network model: data forecasting for the Earth electromagnetic signal before a strong earthquake. *Geoscience Frontiers* 13 (1), 101315. <https://doi.org/10.1016/j.gsf.2021.101315>.
- Hegazy, A.K., Hosni, H.A., El-Sheikh, M.A., Abo-El-Kassem, A., Badawi, E.S., Lovett-Doust, L., 2021. Plant biodiversity and soils in the Jebel Marra region of Darfur, Sudan. *Arid Land Research and Management* 35 (2), 127–161. <https://doi.org/10.1080/15324982.2020.1819913> (2021) Apr 3.
- Hido, A., Tolera, M., Lemma, B., Evangelista, P.H., 2020. Population status and resin quality of frankincense *Boswellia neglecta* (burseraceae) growing in South omo, southwestern Ethiopia. *Journal of Sustainable Forestry* 39 (6), 620–634. <https://doi.org/10.1080/10549811.2020.1721302> (2020).
- IPBES. (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Version 1). Zenodo. <https://doi.org/10.5281/zenodo.6417333>.
- Ismail, I.M., Elawad, A.A., 2015. Phytosociological analysis and species diversity of herbaceous layer in Rashad and Alabassia localities, South Kordofan State, Sudan. *Jordan Journal of Biological Sciences* 8 (2), 151–157. <https://doi.org/10.12816/0027562> (2015) Jun 1.
- Ismail, M.I., 2020a. Changes in ecological parameter of woody vegetation along altitudinal gradient in Jebel El-Dair. *North Kordofan, Sudan. Forest Res.* 9, 228 (2020).
- Ismail, I.M., 2020b. Phytosociology and biodiversity indices of the Woody plants of Alfula Area, West Kordofan, Sudan. *Agriculture and Forestry Journal* 4 (1), 40–46 (2020) Feb 28.
- Ismail, I.M., 2021. Ecological assessment of the woody vegetation, along canopy and regeneration layers in Al Galabat District, Al Gedarif State, Sudan. *Agriculture and Forestry Journal* 15–24 (2021) 5 (August).
- Ismail, I.M., ElSheikh, E.A., 2016. Floristic composition, phytosociology and species diversity of Woody vegetation of Jebel AlGerri, Blue Nile State, Sudan. *JOUR. OF NAT. RESOUR. & ENVIRON. STU* 4 (2), 24–34 (2016).
- Magid, T.D.A., Eltayb, M.T.A., Dirar, A.M.A., 2014. Equalizing gum codal term (a Code E414), of Acacia senegal (L) with Acacia seyal (Del.), and its impact on gum production and exportation. *Journal of Applied and Industrial Sciences* 2 (3), 144–151.
- Millennium Ecosystem Assessment, 2005. Dryland systems. In: *Ecosyst. Hum. Well-being Carr. State Trends*, pp. 623–662 (2005).
- Mishra, N.B., Crews, K.A., 2014. Mapping vegetation morphology types in a dry savanna ecosystem: integrating hierarchical object-based image analysis with random forest. *Int. J. Remote Sens.* 35 (3), 1175–1198. <https://doi.org/10.1080/01431161.2013.876120> (2014).
- Mishra, A.K., Bajpai, O., Sahu, N., Kumar, A., Behera, S.K., Mishra, R.M., Chaudhary, L. B., 2013. Study of plant regeneration potential in tropical moist deciduous forest in northern India. *International Journal of Environment* 2 (1), 153–163. <https://doi.org/10.3126/ije.v2i1.9218>.
- Mohammed, E.M., Hamid, E.A., Ndakidemi, P.A., Treydte, A.C., 2022. The stocking density and regeneration status of Balanites aegyptiaca in Dinder Biosphere Reserve, Sudan. *Trees, Forests and People* 8, 100259. <https://doi.org/10.1016/j.tfp.2022.100259> (2022) Jun 1.
- Mohammed, E.M., Hassan, T.T., Idris, E.A., TD, Abdel-Magid, 2021. Tree population structure, diversity, regeneration status, and potential disturbances in Abu Gadaf natural reserved forest. Sudan. *Environmental Challenges* 5, 100366. <https://doi.org/10.1016/j.envc.2021.100366> (2021) Dec 1.
- Mutowo, G., Murwira, A., 2012. The spatial prediction of tree species diversity in savanna woodlands of Southern Africa. *Geocarto Int* 27 (8), 627–645. <https://doi.org/10.1080/10106049.2012.662530> (2012) Dec 1.
- Neelo, J., Teketay, D., Kashe, K., Masamba, W., 2015. Stand structure, diversity and regeneration status of woody species in open and enclosed dry woodland sites around Molapo farming areas of the Okavango Delta, Northeastern Botswana. *Open Journal of Forestry* 5 (4), 313–328. <https://doi.org/10.4236/ojfor.2015.54027> (2015) Mar 20.
- Niinemets, Ü., Valladares, F., 2004. Photosynthetic acclimation to simultaneous and interacting environmental stresses along natural light gradients: optimality and constraints. *Plant Biol.* 6 (03), 254–268. <https://doi.org/10.1055/s-2004-817881> (2004) May.
- Nikiema, A., 2005. Agroforestry Parkland Species diversity: Uses and Management in Semi-Arid West-Africa (Burkina Faso). Wageningen University and Research. <https://doi.org/10.18174/121636> (2005).
- Ouédraogo, A., Thiombiano, A., 2012. Regeneration pattern of four threatened tree species in Sudanian savannas of Burkina Faso. *Agroforestry Systems* 86, 35–48.
- Pereira, H.M., Cooper, H.D., 2006. Towards the global monitoring of biodiversity change. *Trends Ecol. Evol. (Amst.)* 21 (3), 123–129. <https://doi.org/10.1016/j.tree.2005.10.015> (2006) Mar 1.
- Ratter, J.A., Bridgewater, S., Ribeiro, J.F., 2003. Analysis of the floristic composition of the Brazilian cerrado vegetation III: comparison of the woody vegetation of 376 areas. *Edinburgh journal of botany* 60 (1), 57–109. <https://doi.org/10.1017/S0960428603000064> (2003) Mar.
- Romero-Ruiz, M.H., Flantua, S.G., Tansey, K., Berrio, J.C., 2012. Landscape transformations in savannas of northern South America: land use/cover changes since 1987 in the Llanos Orientales of Colombia. *Applied Geography* 32 (2), 766–776. <https://doi.org/10.1016/j.apgeog.2011.08.010> (2012) Mar 1.
- Rozendaal, D.M., Chazdon, R.L., 2015. Demographic drivers of tree biomass change during secondary succession in northeastern Costa Rica. *Ecological Applications* 25 (2), 506–516. <https://doi.org/10.1890/14-0054.1> (2015) Mar.
- Schmidt, M., Veldkamp, E., Corre, M.D., 2015. Tree species diversity effects on productivity, soil nutrient availability and nutrient response efficiency in a temperate deciduous forest. *For. Ecol. Manage.* 338, 114–123. <https://doi.org/10.1016/j.foreco.2014.11.021> (2015) Feb 15.
- Schroth, G., Harvey, C.A., 2007. Biodiversity conservation in cocoa production landscapes: an overview. *Biodivers. Conserv.* 16, 2237–2244. <https://doi.org/10.1007/s10531-007-9195-1> (2007) Jul.
- Shirima, D.D., Totland, Ø., Munishi, P.K., Moe, S.R., 2015. Relationships between tree species richness, evenness and aboveground carbon storage in montane forests and miombo woodlands of Tanzania. *Basic Appl Ecol* 16 (3), 239–249. <https://doi.org/10.1016/j.baae.2014.11.008> (2015) May 1.
- Shukla, P.R., Skeg, J., Buendia, E.C., Masson-Delmotte, V., Pörtner, H.O., Roberts, D.C., ... & Malley, J. (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.
- Siddig, A.A., 2014. Biodiversity of Sudan: between the harsh conditions, political instability and civil wars. *Biodivers J* 5 (4), 545–555.
- Siddig, A.A., 2019. Why is biodiversity data-deficiency an ongoing conservation dilemma in Africa? *Journal for Nature Conservation* 50, 125719. <https://doi.org/10.1016/j.jnc.2019.125719> (2019) Aug 1.
- Sobola, O.O., Oke, D.O., Adedayo, A.G., Olusola, J.A., 2021. Tree species composition, richness and diversity in the Northern Guinea-Savanna Taraba State, Nigeria. *Asian Journal of Research in Agriculture and Forestry*. 7 (4). <https://doi.org/10.9734/ajraf/2021/v7i430133> (2021) Sep 10-1.
- Su, D., Yu, D., Zhou, L., Xie, X., Liu, Z., Dai, L., 2010. Differences in the structure, species composition and diversity of primary and harvested forests on Changbai Mountain,

- Northeast China. *Journal of forest science* 56 (6), 285–293. <https://doi.org/10.17221/84/2009-JFS> (2010).
- Sylla, D., Leroux, L., Ndao, B., Lo, A., Mbow, C., Diouf, A.A., 2025. Woody species diversity as a function of land use types and environmental factors in agroforestry landscapes of Senegal [Preprint] (2025). Research Square. <https://doi.org/10.21203/rs.3.rs-6261997/v1>.
- Teketay, D., 2005. Seed and regeneration ecology in dry afro-montane forests of Ethiopia: I. Seed production-population structures. *Trop Ecol* 46 (1), 45–64.
- Ter Steege, H., Pitman, N.C., Do Amaral, L.L., de Souza Coelho, L., de Almeida Matos, F. D., de Andrade Lima Filho, D., Salomão, R.P., Wittmann, F., Castilho, C.V., Guevara, J.E., Veiga Carim, M.D., 2023. Mapping density, diversity and species-richness of the Amazon tree flora. *Communications biology* 6 (1), 1130. <https://doi.org/10.1038/s42003-023-05514-6> (2023) Nov 8.
- Tindano, E., Ganaba, S., Thiombiano, A., 2014. Composition floristique et état des peuplements ligneux des inselbergs suivant un gradient climatique au Burkina Faso (Afrique de l'Ouest). *Fl Veg Sudano-Sambesica* 17, 9–27.
- Tindano, E., Ganaba, S., Sambare, O., & Thiombiano, A. (2015). Sahelian inselberg vegetation in Burkina Faso. [10.19182/bft2015.325.a31270](https://doi.org/10.19182/bft2015.325.a31270).
- Tutu, S.O., Adam, H.E., Mohammed, M.H., Koli, A.O., Juumma, I.A., Eltahir, M.E., Abdelrahman, H.A., 2019. Species composition, structure and diversity of woody vegetation at El-Salam Locality, West Kordofan, Sudan. License This work is licensed under a Creative Commons Attribution 4.0 International License 20, 172–180 (2019).
- Vanderhaegen, K., Verbist, B., Hundera, K., Muys, B., 2015. REALU vs. REDD+: carbon and biodiversity in the afro-montane landscapes of SW Ethiopia. *For. Ecol. Manage.* 343, 22–33. <https://doi.org/10.1016/j.foreco.2015.01.016> (2015) May 1.
- Warth, B., Marohn, C., Asch, F., 2020. Modelling land use change effects on ecosystem functions in African Savannas—A review. *Glob Food Sec* 26, 100421 (2020) Sep 1.
- Western, D., Russell, S., Cuthill, I., 2009. The status of wildlife in protected areas compared to non-protected areas of Kenya. *PloS one* 4 (7), e6140. <https://doi.org/10.1371/journal.pone.0006140> (2009) Jul 8.
- Woinarski, J.C., Armstrong, M., Brennan, K., Fisher, A., Griffiths, A.D., Hill, B., Milne, D. J., Palmer, C., Ward, S., Watson, M., Winderlich, S., 2010. Monitoring indicates rapid and severe decline of native small mammals in Kakadu National Park, northern Australia. *Wildlife Research* 37 (2), 116–126. <https://doi.org/10.1071/WR09125> (2010) Apr 16.
- Yakubu, M., Saka, M.G., Sa'idu, I., Mahmud, W.A., Yunus, A.U., 2020. Assessment of the checklist and regeneration status potential of species seedlings and saplings of Baturiya Hadejia Wetland Game Reserve, Jigawa State, Nigeria. *Glob Adv Res J Agric Sci* 9, 19–26 (2020).
- Yasin, E.H., Mulyana, B., 2022. Spatial distribution of tree species composition and carbon stock in Tozi tropical dry forest, Sinnar State, Sudan. *Biodiversitas Journal of Biological Diversity* 23 (5). <https://doi.org/10.13057/biodiv/d230513> (2022) Apr 25.
- Young, N.E., Romme, W.H., Evangelista, P.H., Mengistu, T., Worede, A., 2017. Variation in population structure and dynamics of montane forest tree species in Ethiopia guide priorities for conservation and research. *Biotropica* 49 (3), 309–317. <https://doi.org/10.1111/btp.12420> (2017).