



Exploring tree diversity and stand structure of savanna woodlands in southeastern Sudan

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Abstract: Savanna woodlands in Sudan host great biodiversity, provide a plethora of ecosystem goods and services to local communities, and sustain numerous ecological functions. Although the importance of the *Acacia* trees in these areas is well known, up-to-date information about these woodlands' diversity is limited and changes in their woody vegetation composition, density, diversity and relative frequency are not monitored over time. This study explored tree diversity and stand stage structure in Nuara Reserved Forest, a typical savanna woodland ecosystem in southeastern Sudan. A total of 638 circular sample plots (1000 m² for each) were established using a systematic sampling grid method. The distance between plots was 200 m. In each plot, all living trees with diameter at breast height (DBH) ≥ 5.00 cm were identified and counted, and their DBH values were recorded. From these data, tree composition, diversity, density and stage structure were assessed. There were 12,259 individual trees representing four species (*Acacia seyal*, *Balanites aegyptiaca*, *Acacia Senegal* and *Acacia mellifera*) that belong to two families. The dominant species was *Acacia seyal*. Average tree density was 191 trees/hm² and the Shannon-Weiner index for trees diversity was 0.204. Overall, young trees comprised 86.30% of the forest. The state of tree richness and density in the study area was low compared to other similar environments in the region and around the world. We recommended adoption of a proper management system that includes monitoring of woody vegetation diversity in this forest, and management actions to enhance tree diversity and sustain ecosystem services to local communities. In addition to care for the dominant *Acacia seyal* stands, more attention and conservation should be devoted to reestablishing *Acacia senegal* and *Acacia mellifera* trees because of their high ecological and economic values for local communities.

Keywords: species diversity; stand structure; savanna woodland ecosystem; forest monitoring; forest management; ecosystem services; Nuara Reserved Forest

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1 Introduction

Forests and savanna woodlands contribute ecosystem services such as providing wildlife habitat, safeguarding against erosion and desertification, contributing to soil fertility, and many others (FAO, 2016). Sudan is characterized by five climatic zones, which extend from the desert in the far north to the savanna in the south. The Sudan's Fifth National Report to the Convention on Biological Diversity (HECNR, 2014) and the Sudan's National Biodiversity Strategy and Action

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Plan 2015–2020 (NBSAP, 2015) stated that forests cover 11.9% of the total country area and are considered rich in terms of ecosystem and species diversity.

The forest resources substantially contribute to Sudan's society, economy and environment (Abdel Nour, 2013; Siddig et al., 2019a). However, forests of Sudan are threatened by deforestation, which is motivated primarily by energy needs and land clearance for agricultural expansion. Furthermore, Bakr et al. (2018) stated that the distribution of these resources is unbalanced (i.e., the greatest amount of the remaining forests is distributed in the south, whereas the poor and sparse woody formations characterize the northern part of Sudan where more people are concentrated and the need for forest goods and services is highest). Forest cover degraded from about 40% to 10% in Sudan over the last 110 years. The Forest National Corporation (Abdel Nour, 2013) reported that the desert and semi desert zones cover about 62.0% of Sudan's land area, of which 88.1% is classified as dry lands. In response to this unprecedented decline of vegetation cover and biodiversity, many conservation efforts were initiated over the last decade, including establishing biodiversity institutions and protected areas, developing the National Biodiversity Strategy and Action Plan 2015–2020, and signing and ratifying of several regional and international agreements (Siddig et al., 2019a).

Despite these significant steps toward the protection of forests and forest action plans, establishing a forest monitoring system remains an essential need. Forest monitoring programs provide information on the status of forests and habitats and are a central process in applying proper sustainable forest management (Millennium Ecosystem Assessment, 2005). Forest monitoring can rigorously estimate potential ecosystem goods and services. Repeated forest assessments based on responses of plants and changes of species composition can be used to evaluate environmental quality and changes over time in response to forest management (Ferris-Kaan and Patterson, 1992; Siddig et al., 2016). Vardon and Harris (2017) recognized five indicators of forest ecosystem condition: vegetation, biodiversity, soil, water and carbon. Furthermore, forest monitoring is also regarded as international commitment. For instance, the Convention on Biological Diversity (CBD) highlighted the necessity of monitoring ecosystems, habitats, species, communities and genes (Spellerberg, 2005).

Despite monitoring is important for proper forest management, it faces many challenges worldwide. In Europe, the definitions, approaches and scope of monitoring are continuous challenges that result in collections of forest information are not uniform and problematic, so it is hard to make conclusions over time and place (Vidal et al., 2016). In China, forest inventory and monitoring programs face difficulties in obtaining information across large areas and high costs (Zhang et al., 2018). Shuaibu and Dagba (2016) stated that in Nigeria, forest monitoring faces many challenges such as site access and inadequate technology, equipment and funds.

Sometimes, monitoring is motivated by the economic value of the products that the forest holds. For example, stands of gum arabic producing trees (GAPTs) (i.e., *Acacia senegal* and *Acacia seyal*) are considered the most important wooded lands in Sudan for their tremendous economic value to the national economy and local communities' livelihoods. Hence, FNC gives these stands special focus including their management, gum production and threat control. Nevertheless, current reports and field observations indicated a substantial decline in both the abundance of GAPTs and gum production primarily due to a massive expansion of mechanized rain fed agriculture that converts forests to agricultural lands as well as drought events in recent years (Bakr et al., 2018). Moreover, Siddig (2014) warned about the potential impacts of instability and conflicts on forest resources in Sudan, particularly in and around the gum Arabic belt (i.e., Darfur and Kordofan) where vast natural stands of GAPTs exist.

Quantitative knowledge about basic stand diversity and structure, and stand health indicators such as canopy health and density of dead standing trees is required for these current efforts toward attaining proper management and use of GAPTs to be successful. Unfortunately, due to the absence of regular and long-term monitoring programs, Sudan currently lacks these vital forest condition indicators in most GAPTs stands (Siddig, 2019b). Consequently, management and conservation planning are based on rough estimates. Baillie et al. (2008) stated that in order to create effective

forest management plans, it is obligatory to know which species are present, their relative abundance and species-specific stages, and what factors control their future persistence and dynamics. Clearly, the answer to these questions requires development and adoption of systematic and regular forest monitoring activities as part of the management plans. These forest monitoring programs will not only provide crucial information about current conditions and signals of future trends, but also lay the basis for rational and sustainable use of forests' ecosystem services and goods.

Therefore, the aim of this study is to assess tree diversity and stage structure in Nuara Reserved Forest (a typical savanna woodland ecosystem in southeastern Sudan), as recommended by Siddig (2014) and the Sudan's Fifth National Report to the Convention on Biological Diversity (HECNR, 2014). Specific objectives include (1) establishing basic information about the current condition of Nuara Reserved Forest including species composition, diversity, density and stage structure; (2) discussing the significance of monitoring results in planning forest utilization, conservation and management; and (3) developing a protocol for future monitoring program in Nuara Reserved Forest and other similar natural forests in Sudan.

2 Study area and methods

2.1 Study area

This study was conducted in Nuara Reserved Forest, which is located in Sennar State, Sudan and approximately 360 km southeast of the capital Khartoum (Ahmed et al., 2015). The forest covers an area of 2.56×10^3 hm^2 , and lies between $12^\circ 20' - 12^\circ 26' \text{N}$ and $34^\circ 05' - 34^\circ 08' \text{E}$ (Mohammed, 2018). It is situated in southeastern Sudan and shares borders with Gezira State to the north, Blue Nile State to the south, Gedaref State to the east and White Nile State to the west (Fig. 1). The region's climate is tropical with the year separated into very humid and rainy autumns, intensely dry winters and hot summers. Winter months (December and January) are relatively cold, with temperatures ranging from 16°C to 20°C . From March to November, the climate is very hot (temperature range of $35^\circ \text{C} - 41^\circ \text{C}$). The precipitation is motivated by South Atlantic and Congo air masses with little or no influence from the Indian Ocean. The precipitation increases in the southeast with the total annual precipitation between 300 and 700 mm. Most precipitation falls between June and October, with a peak in August (Gadallah, 2019).

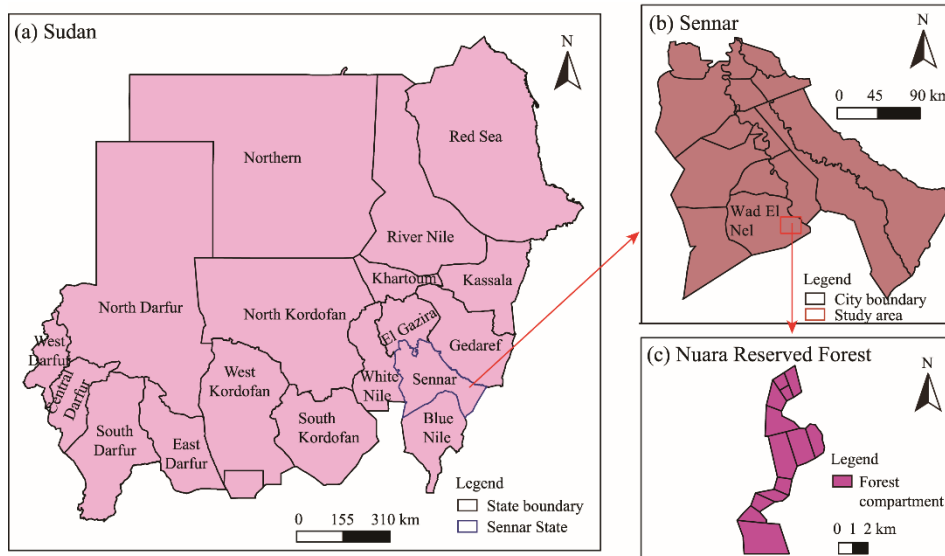


Fig. 1 Sketch maps for the location of Sennar State in southeastern Sudan (a) and the location of Nuara Reserved Forest (study area) in Sennar State (b), as well as the overview of Nuara Reserved Forest (c)

2.2 Study design and field measurement

The data used in this study belong to the Faculty of Forestry, University of Khartoum, which were

produced from a student training course on the formulation of forest management plans that were conducted in Nuara Reserved Forest. In February 2018, 638 circular sample plots were determined in the systematic sampling grid using ArcGIS software (Fig. 2). The grid consisted of several parallel survey lines spaced 200 m apart. Along each survey line, circular plots were located every 200 m, and the area of each was approximately 1000 m² (radius=17.84 m). The first plot in the line was usually located 100 m away from the edge to avoid edge effect. All living trees with diameter at breast height (DBH) ≥ 5.00 cm were identified to species and counted. Their DBH and height were measured using calipers and altimeters, respectively.

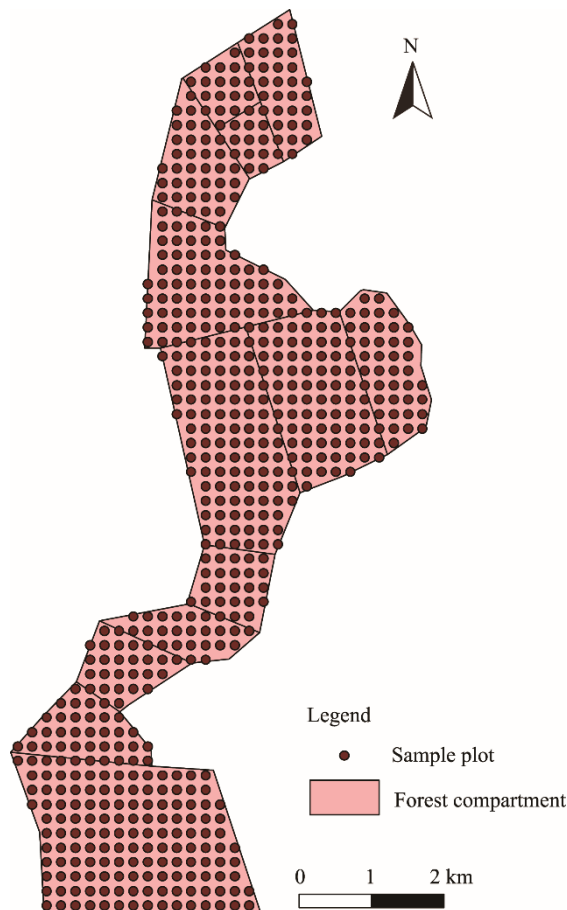


Fig. 2 Distribution of sample plots in Nuara Reserved Forest

2.3 Data analyses

Data were organized in a classic site (plot)-by-species table, and then species richness, tree diversity and tree density were computed in the R software (version 3.5.1) using the vegan: Community Ecology Package (R Core Team, 2015). We computed all analyses based on the plot level data. Species richness is the number of trees species in each plot and for the forest overall, and tree diversity was computed using Shannon-Weiner diversity index (H' ; Eq. 1) (Shannon and Weiner, 1963):

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

where H' is the Shannon-Wiener diversity index; i is the proportion of individuals belonging to species i ; s is the number of tree species; and p_i is the importance value of a species as a proportion of all species i in each sample plot.

The DBH values were used to classify the trees into different stage classes and then the stage

classes were computed in ArcGIS platform. Based on the homogeneity of the study area, we classified the stage of trees into three categories: young (DBH: 5.00–14.99 cm), pre-mature (DBH: 15.00–24.99 cm) and mature (DBH: ≥ 25.00 cm).

3 Results

3.1 Species richness and diversity

From surveys of 638 sample plots in Nuara Reserved Forest, we found 12,259 living trees representing four species (*Acacia seyal*, *Balanites aegyptiaca*, *Acacia Senegal* and *Acacia mellifera*) which belong to two families: Mimosaceae (three species) and Balanitaceae (one species) (Table 1). *Acacia seyal* was the most abundant and dominant species, with 11,638 individuals. We also identified 577 trees for *Balanites aegyptiaca*, 40 trees for *Acacia senegal* and only 4 trees for *Acacia mellifera* in the entire forest. The average tree diversity in Nuara Reserved Forest was 0.204 as computed by Shannon-Wiener diversity index, which was very low.

Table 1 Estimates of trees species composition, relative frequency, number of individuals and relative density in Nuara Reserved Forest

No.	Species name	Number of plots ^a	Relative frequency (%)	Number of individuals	Relative density (trees/hm ²)
1	<i>Acacia seyal</i>	533	84.20	11,638	218.34
2	<i>Balanites aegyptiaca</i>	176	27.80	577	32.78
3	<i>Acacia senegal</i>	15	2.36	40	26.60
4	<i>Acacia mellifera</i>	2	0.31	4	20.00
Total		638 ^b	100.00	12,259	

Note: ^a, number of sample plots where species present; ^b, total number of surveyed plots.

3.2 Tree density and frequency

Average tree density was 191 trees/hm² in the entire forest. Relative density was highest for *Acacia seyal* (218.34 trees/hm²; Fig. 3), followed by *Balanites aegyptiaca* (32.78 trees/hm²), *Acacia Senegal* (26.60 trees/hm²) and *Acacia mellifera* (20.00 trees/hm²). As shown in Figure 4, the spatial pattern of tree density showed that more than 90% of the forest area had medium to high tree density (green and red regions) whereas relatively small areas in the northern tip of the forest were characterized by low tree density (yellow regions).



Fig. 3 Photo showing very dense sample plot dominated by *Acacia seyal* trees in Nuara Reserved Forest

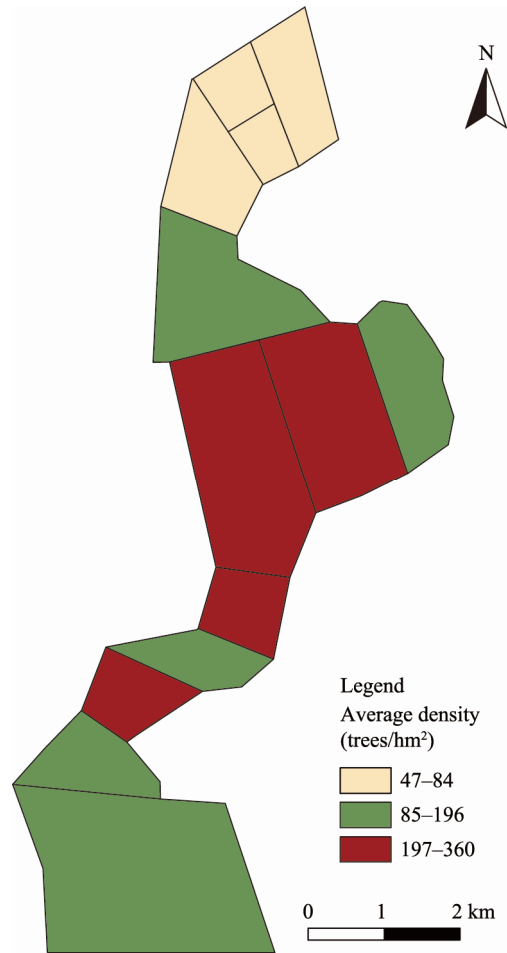


Fig. 4 Spatial distribution of average tree density in Nuara Reserved Forest. The black lines within the figure represent the boundaries of forest compartments.

Species occurrence and distribution in the forest area as measured by their relative frequency indicated that *Acacia seyal* was the dominant species in the forest (Table 1). It occurred in 84.20% of the forest, followed by *Balanites aegyptiaca*, which distributed in 27.80% of the forest. In contrast, *Acacia Senegal* and *Acacia mellifera* were only present in 2.36% and 0.31% of the forest, respectively.

3.3 Tree stage structure

We used three diameter classes to describe forest stage structure, and the results are shown in Table 2. Trees with DBH ranging from 5.00 to 14.99 cm were considered as young/juveniles stage-class, which accounted for 86.30% of the forest trees. Pre-mature tree stage-class, which included trees with DBH of 15.00–24.99 cm, represented 13.35% of the total trees. Lastly, only 0.34% of the total trees had a DBH greater than 25.00 cm and was considered as mature stage-class.

The species-specific stage structure indicated that young trees dominated all species. As shown in Table 2, young stage-class trees comprised 100.00%, 93.10%, 90.00% and 56.49% of *Acacia mellifera*, *Acacia seyal*, *Acacia Senegal* and *Balanites aegyptiaca* trees, respectively.

4 Discussion

In the present study, there were only four species detected with an overwhelming dominance of *Acacia seyal* and notable rarity of *Acacia mellifera*. While this number of species was similar to other forests in this transitional zone with precipitation between low and high, it was much lower

Table 2 Percentage of each species in the three tree stand stages in Nuara Reserved Forest

No.	Species	Number of trees	Percentage of species in the stage (%)		
			Young (5.00–14.99 cm)	Pre-mature (15.00–24.99 cm)	Mature (≥25.00 cm)
1	<i>Acacia seyal</i>	11,638	93.10	6.40	0.42
2	<i>Balanites aegyptiaca</i>	577	56.49	36.56	6.93
3	<i>Acacia Senegal</i>	40	90.00	10.00	0.00
4	<i>Acacia mellifera</i>	4	100.00	0.00	0.00
Total		12,259	86.30	13.35	0.34

compared to the species richness found in many dry forests in Africa. For instance, the average number of woody species was 28 in Neotropical continental forests, 48 in Beza Mahafaiyotropic dry forests in Madagascar and 110 in Bereku Forest Reserve, Tanzania (Sussman, 1994). The analysis of the trees in our study area revealed that Nuara Reserved Forest was dominated by one species (*Acacia seyal*), an indicator of change in state of the ecosystem (Thompson, 2011). This dominant may suppress other tree species' natural regeneration in this area. The tree density in Nuara Reserved Forest of Sudan (Table 1) was similar to those in Oban Forest Reserve of Nigeria (306.00 trees/hm²) as reported by Igbinsola and Ejakhe (2015) and in lower-altitude Western Himalayan forests of India (235.00 trees/hm²) as reported by Malik and Bhatt (2015). However, our estimates on tree density in Nuara Reserved Forest were lower than those in Bereku Forest Reserve of Tanzania (616.00 trees/hm²) (Giliba et al., 2011), higher-altitude Western Himalayan forests of India (505.00 trees/hm²) (Malik and Bhatt, 2015) and tropical forests of Costa Rica (446.00 trees/hm²) (Lieberman et al., 1996). Tree species diversity in Nuara Reserved Forest of Sudan ($H'=0.204$) was also lower than those in other forests of Africa (H' ranged from 0.380 in North-East Nigeria to 4.270 in Bereku Forest Reserve of Tanzania). The lower species diversity in the present study could be due to the size of the study area and environmental heterogeneity as well as deforestation activities (Suratman, 2012). The low values of tree density and diversity compared to other locations may reflect dissimilarity in precipitation, soil characteristics and landscape in addition to differences in sampling intensity (Wakawa et al., 2017).

Nuara Reserved Forest greatly contributes to the livelihood of the local communities by providing forest fruits, fallen wood for fuel, forage and crops, and job opportunities (Mohammed, 2018). This study identified some ecological information about the dominant species *Acacia seyal*, which provides great economic benefits in the region, including the production of charcoal and gum Arabic. It also offers basic information about the current condition of the forest, including species composition, tree diversity, tree density and stage structure, which will help in establishing rigorous future monitoring programs and inform conservation efforts. Overall, this study provides information and insights for guiding forest biodiversity restoration and implementing sustainable forest management activities in the savanna woodlands.

5 Conclusions and recommendations

Forest tree diversity, dominant tree species, tree density and tree stage structure are key data needed to design ecosystem management for environmental conservation for a given region. This study showed low tree diversity (0.204) in Nuara Reserved Forest of southeastern Sudan. The forest included only four species (*Acacia seyal*, *Balanites aegyptiaca*, *Acacia senegal* and *Acacia mellifera*), which typically occur in the savanna woodlands. *Acacia seyal* was the most abundant species in the Nuara Reserved Forest while *Acacia mellifera* was very rare. Nuara Reserved Forest may be considered young forest because 86.30% of the trees were in the young stage-class (DBH: 5.00–14.99 cm). The state of tree species richness and relative density in the study area was low compared to similar environments in the world.

To secure a sustainable supply of goods and services from Nuara Reserved Forest to local communities while to maintain the highest forest ecological integrity, we suggest implementation

of the following management interventions: (1) prioritizing the restoration of *Acacia Senegal* and *Acacia mellifera* because they are currently rare species and are at risk of extinction in this area and also because they have high ecological and economic values for local communities; (2) considering the establishment of a comprehensive long-term monitoring program through permanent sample plots in this forest to provide time series data that are essential to assess the overall ecosystem state and evaluate the dynamics of tree populations and the changes of savanna ecosystems; and (3) conducting in-depth research studies that focus on the resilience of savanna ecosystems to climate change and variability, and on the drivers of deforestation that causes the decline of woody vegetation diversity in the savanna woodlands of southeastern Sudan. Since our primary objective in this study is to explore nature and we are limited by the available data, we recommend that future work should focus on revealing relationships and trends of diversity metrics as a function of environmental conditions in the region.

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