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DIVERSITY AND STRUCTURE OF *KHAYA SENEGALENSIS* (DESR.) A.JUSS HABITATS ALONG PHYTOGEOGRAPHICAL ZONES IN CHAD (CENTRAL AFRICA): IMPLICATIONS FOR CONSERVATION AND SUSTAINABLE USE

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Abstract

In Chad, the species of *Khaya senegalensis* is commonly used by the local communities to treat several diseases such as malaria, fever and cough. However, the species is facing the greatest threat for the survival due to its exploitation as timber. The species is on the IUCN red list with endangered status locally. Thus, this study assessed the population structure and ecological indicators of vegetation in three climatic zones dominated by *Khaya senegalensis* in Chad as a basis for sustainable management and conservation strategies. A total of 88 plots (30 m x 30 m) were used in three phytogeographical zones for data collection. The structural parameters (tree density, basal area) and ecological indicators (specific richness, Shannon diversity index, Pielou's evenness index, importance value index) were assessed for all tree species and for *Khaya senegalensis* following a climatic gradient. A number of 300 tree species belonging to 66 families, 11 life form and 14 chorological types were inventoried. *K. senegaleensis* had the highest significance value index across all three climate zones. In terms of vegetation characteristic, Sudano-Guinean and Sudanian zones were similar against Sudano-Sahelian zone which was different. These results should be fundamental for the conservation and sustainable management of *K. senegalensis* and its habitats specially in Chad. Likely, the findings contribute to knowledge addition for the species conservation. However, the methodological limitations related to sampling should not be obscured. Therefore, the species' abundance areas were randomly identified while plots were placed stratified.

Keywords: *Khaya senegalensis*, climatic zones, floristic composition, stands density, vegetation structure, Chad

INTRODUCTION

Natural resources play a particular and vital role for local communities in sub-Saharan Africa, which use them as sources of energy, human and animal food in addition to their role in regulating agro-climatic conditions. (Sourou et al. 2016 ; Hamawa et al. 2018). The human population growth and the search for arable land have led to the modification and fragmentation of natural habitats and ecosystems leading to the isolation and extinction of natural stands (Smith and Hellmann, 2002 ; Feeley and Terborgh, 2008 ; Assongba et al. 2014). Moreover, overexploitation of natural resources has led to the decline and disappearance of species with high genetic and socio-economic potential (Assongba et al. 2014). *Khaya senegalensis* (Desr.) A.Juss, belonging to the *Meliaceae* family, is indigenous to Africa and is commonly known by various names such as African mahogany, dry zone mahogany, Gambia mahogany, khaya wood, Senegal mahogany, cailcedrat, acajou, djalla, and bois rouge. This tree species is noted for its rapid growth, typically reaching a medium-sized stature with heights ranging from 15 to 30 meters and a diameter of around 1 meter. Its bark presents hues ranging from dark grey to grey-brown, while its heartwood exhibits a brown coloration enriched with a pink-red pigment and characterized by coarse interlocking grains. The foliage of *Khaya senegalensis* is recognizable for its spiral arrangement of leaves clustered at the branch ends. Its fragrant white flowers are accompanied by fruit that transitions from grey to black as it ripens (World Conservation Monitoring Centre, 1998).

Khaya senegalensis, widely distributed in sub-Saharan savannahs, is under this pressure. In Chad, the species contributes to the survival of many people in rural areas (Langa 2016). Its bark, wood, leaves, roots and seeds are widely exploited by the population for various uses (Langa 2016). It is traditionally used to treat several diseases and symptoms. However, in recent years with the population explosion and impoverishment in rural areas leading to the overexploitation of elderly subjects, serious threats weigh on the species. Therefore, the International Union for Conservation of Nature (IUCN) classified the species in 2019 on its red list among vulnerable species (IUCN 2019). *Khaya senegalensis* is also threatened by habitat loss due to the rapid fragmentation and loss of its forest ecosystems (Langa 2016; Issa et al. 2018).

The literature review revealed several gaps of knowledge on the species in Africa and particularly in Chad. In the current context, climate change, deforestation, habitat fragmentation and anthropogenic pressures threaten the survival of most useful woody species, assessing the dendrometric structure and the ecology of the populations of these species is fundamental. The establishment of a strategy for the sustainable management and conservation of forest genetic resources cannot be achieved without a better knowledge of the ecology of species in addition to genetic aspects (Houètchégnon 2016). Thus, the study does not only define a sustainable management and conservation strategy for *K. senegalensis* in Chad, but also helps to fill the knowledge gap on the species in general.

The density, diameter and height structure of a stand are important structural parameters for characterizing the demography of a forest stand (Herrero-Jáuregui et al. 2011; Awé et al. 2020). According to Wulder et al. (2009), forest structure studies help assess the state of degradation of ecosystems and understand the history of past management and forest dynamics. Hitimana et al. (2004) and Sourou (2017) also showed that these studies can help identify the types of development to be applied. Regarding current pressures on the species in Chad, a study of its stands structure should be essential and justified in order to assess the conditions and to help establish an adequate management policy. The objective of the study is to examine the structure and ecology of K. senegalensis stands within Chad. It focuses on analyzing the floral composition and ecological traits of natural K. senegalensis stands across three distinct climate zones. Additionally, the study evaluates the dendrometric structure of three stands' community and *K. senegalensis* populations within the corresponding three climate zones in Chad. The study seeks to answer the following fundamental questions: 1) what are the dendrometric characteristics of the tree stands and *K. senegalensis* species population in the different climate zones? 2) how does the structure of the species stand and population vary from one climate zone to another? 3) what are the ecological indicators of the species vegetation groups?

MATERIAL AND METHODS

Study areas

The research took place within the native habitat of K. senegalensis in Chad. This area is located between 8°00 'and 12°00' N and 14°00 'and 24°00' E. It extends over two regional endemic centers, namely Sudanian and Guinean and the Sudano-sahelian transition zone (White 1986). The climate is tropical with summer rains, and annual rainfall between 800 mm and 1300 mm (Fig. 1). The three climatic zones are generally characterized by ferruginous soil, vegetation mainly made up of wooded savannah, a dry climate with a temperature of up to 42°C (Table 1).

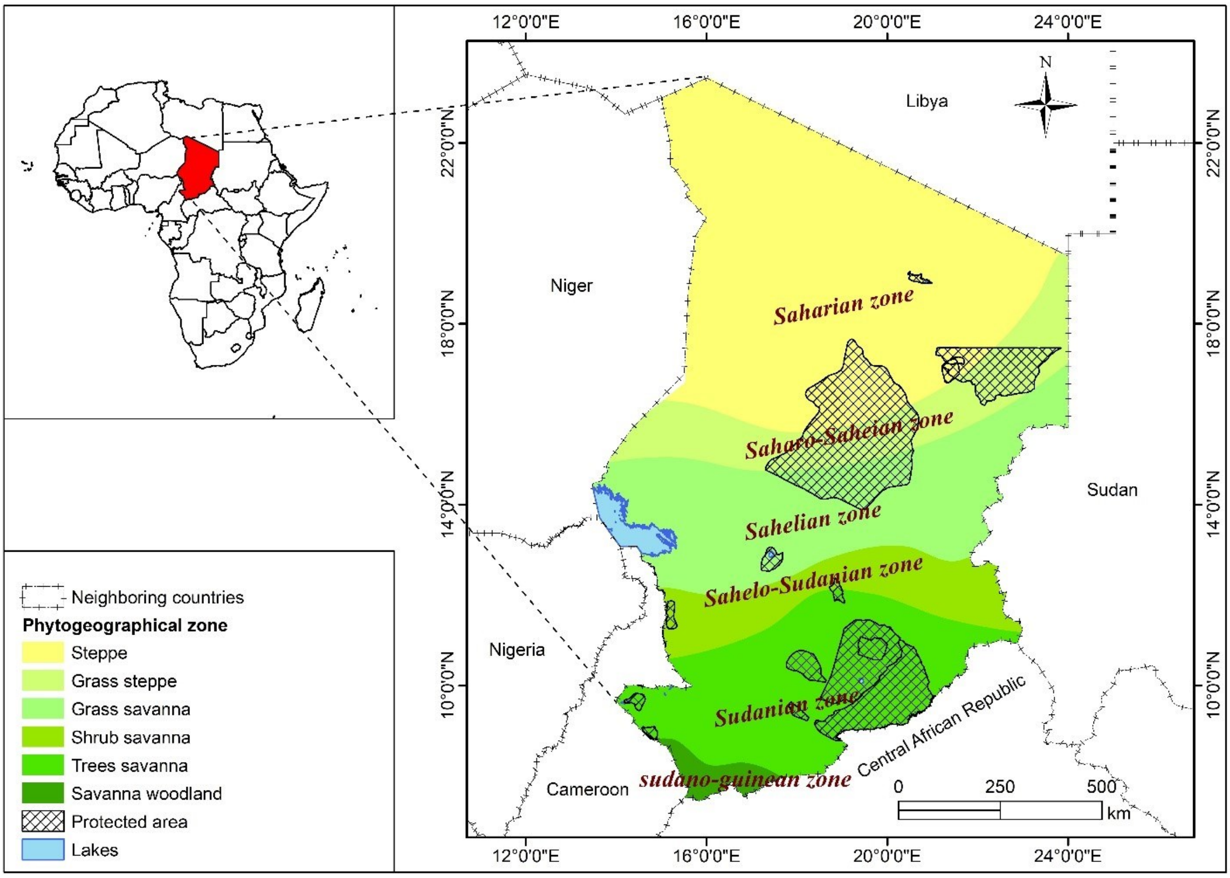

Fig.1 Map of phytogeographical zones in Chad

Table 1 Climate, ecological and geological characteristics of three climate zones in Chad

Phyto-geographical zones	Soil types	Climate	Vegetation	Precipitation (mm/year)	Hydrography	Temperature
Sudano-Guinean	Vertisol, tropical ferruginous soils, alkali leached soils, hydromorphic and clay soils	Tropical climate	Wooded savannah and woodland dominated by *Isoberlinia doka* Craib & Stapf., *Prosopis Africana* (Guill. & Perr.), *Khaya senegalensis* (Desr.) A. Juss., *Daniella oliveri* (Rolfe) Hutch. & Dalziel, *Vitellaria paradoxa* C.F.Gaertn. etc.	Unimodal rainy season from May to July, maximum precipitation of 1200 mm	Hydrographic network made up of the Chari (1,200 km) and Legone (1,000 km) rivers which feed lakes Chad, Iro and Wey	The mean maximum temperature is reached in March (35º C-38º C)
Sudanian	Tropical ferruginous soils, Vertisol, or sandy hydromorphic soil		Wooded savannah dominated by *Afzelia Africana* Smith ex Pers., *Prosopis Africana* (Guill. & Perr.), *Khaya senegalensis* (Desr.) A. Juss., *Daniella oliveri* (Rolfe) Hutch. & Dalziel, *Vitellaria paradoxa* C.F.Gaertn., *Sclerocaryon birrea* (A. Rich.) Hochst. etc.	Unimodal rainy season from May to July, maximum precipitation between 800–1200 mm	Hydrographic network made up of the Mayos who feed the Léré, Fianga Tikem and Tréné lakes	The mean maximum temperature is reached in March (39º C-41º C)
Sudano-Sahelian	Tropical ferruginous soils, vertisols with sandy ridges		Savannah with species such as *Khaya senegalensis* (Desr.) A. Juss., *Daniella oliveri* (Rolfe) Hutch. & Dalziel, *Vitellaria paradoxa* C.F.Gaertn., *Monotes kerstingii* Gilg. etc.	Unimodal rainy season from July to August, maximum precipitation between 300–600 mm	-	The mean maximum temperature is reached in March (42º C-43º C)

Sampling

The study was carried out in forests dominated by *K. senegalensis* in the three climatic zones. Square plots of 900 m^2 (30 m × 30 m) have been installed in each climatic zone (Fig. 2). The number (n) of plots inventoried per study area was determined by the formula of Dagnelie (1998).

$$n = \frac{t^2_{1-\alpha/2} \times CV^2}{d^2} \quad (1)$$

CV = coefficient of variation on the mean basal area that was gotten by using the ratio of the standard deviation to the mean. Therefore, during the exploratory mission in each climatic zone, dendrometric measurements were taken in the zones of the distribution and abundance of *K. senegalensis* in order to calculate the average of basal areas; d = margin error of estimate of the mean basal area between 5 and 15%; $t_{1-\alpha/2}$ is the value of the t statistic of the Student distribution for an alpha risk of 0.05; $t_{1-\alpha/2} = 2$.

To inventory of the natural regeneration of *K. senegalensis*, square plots of 5 m x 5 m were installed on the diagonal of the main plot of 30 m x 30 m (Fig. 2).

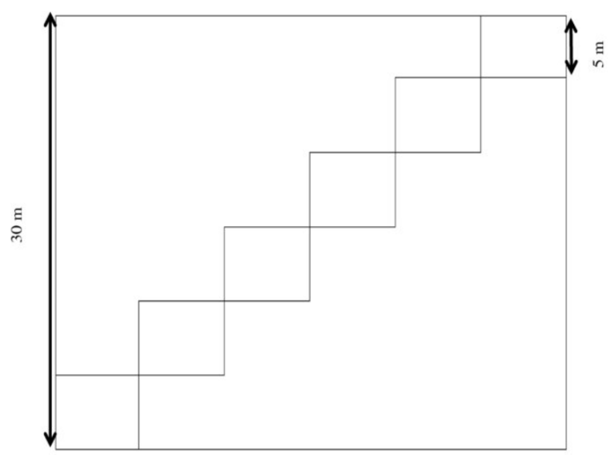

Fig.2 Sample unit of forest inventory

Data collection

Ecological characteristics of habitat types Khaya dominated

Within each plot, a phyto-sociological survey of all woody and herbaceous species was carried out. Then, species and species family nomenclatures were based on APG IV (Angiosperm Phylogeny Group, 2016). Therefore, species abundance and dominance were noted according to Braun-Blanquet (1932). The coefficients were assigned to the species as follows: 5 for mean coverage equal to 87.5% (species covering 75 to 100% of the soil surface); 4 for mean coverage equal to 62.5% (species covering 50 to 75% of the ground surface); 3 for mean coverage equal to 37.5% (species covering 25 to 50% of the ground surface); 2 for mean coverage equal to 15% (species covering 5 to 25% of the soil surface); 1 for mean cover equal to 3% (species covering 1 to 5% of the ground surface); + for mean coverage equal to 0.5% (species covering less than 1% of the ground surface).

Dendrometric and structure of vegetation

The stratified and random sampling technique was considered taking into account the accessibility and uniformity of stands. Data on diameter at breast height (dbh) and total tree height were measured on each individual tree (dbh ≥ 5 cm) in the plots. Small diameter trees (dbh < 5 cm) were considered as regeneration and counted in the 5m x 5m plots installed on the diagonal of the main plot (Fig. 2). The diameter (*d*) of low branched trees (several stems counted before 1.3 m above the ground) was estimated by the quadratic sum of the diameters ds_i (i = 1 to w) of the different stems counted.

$$d = \sqrt{\sum_{i=1}^{w} ds_i^2} \qquad (2)$$

Data Analysis

Ecological characteristics of habitat types Khaya dominated

The biological and phytogeographic types of the different plant groups were determined. The biological types used were those defined by Raunkier (1934). The phytogeographic types were established following the chronological subdivisions of White (1983). The types of vegetation were determined based on the Nomenclature of African vegetation types by Yangambi Agreement (Aubreville 1957; Ganame et al. 2020). A binary data matrix was constructed on the basis of the abundance-dominance data of all the plant species recorded. This matrix has been subjected to "Non-Metric Multidimension Scaling (NMDS)" analysis using R 3.5.1 software (R Core Team 2018) to explore the variation of floristic composition between plots.

In each phytogeographical zone, the specific richness, the Shannon diversity index and the Pielou evenness index were calculated for the type of vegetation. The specific richness (*S*) represents the total number of species. The Shannon's Diversity Index (*H*) is computed using the following formula:

$$H = -\sum_{i=1}^{s} \frac{n_i}{n} log_2 \frac{n_i}{n} \qquad (3)$$

n_i is the number of individuals of species *i*, *n* is the overall number of trees inventoried in the plot.

The Pielou's evenness (*Eq*) measures the diversity degree of a stand compared with the possible maximum and is computed as follow:

$$Eq = \frac{H}{Hmax} \qquad (4)$$

with

$$Hmax = log_2 S \qquad (5)$$

In equation (4), H represents the value of the Shannon diversity index; $Hmax$ was the maximum value of the diversity index and S the number of species recorded in the considered plot.

In addition, a β-Diversity (similarity index of Sorensen) was calculated in order to compare the similarity between different phytogeographical zone. Therefore, Sorensen similarity index is

$$\frac{2c}{(a+c)} \qquad (6)$$

where c is the number of the common species of the different phytogeographical zones, a is the number of species of the first zone and b is the number of species of the second zone. Thereby, Sorensen index varies from 0% (no similarity) to 100% (full similarity).

Dendrometric and structure of vegetation

The following dendrometric parameters were computed general for all vegetation and specifically for *K. senegalensis* along the phytogeographical zones. The tree density (N) is the number of tree individuals per hectare.

$$N = \frac{n}{s} \qquad (7)$$

n is the total number of trees (or number of *K. senegalensis* trees) in the plot and s the area of the plot (s = 0.09 ha).

The stand basal area (G), i.e. the sum of the cross-sectional area at 1.3 m above the ground level of all trees in a plot, was expressed in m^2/ha:

$$G = \frac{\pi}{4s} \sum_{i=1}^{n} 0.0001 di^2 \qquad (8)$$

di is the diameter (in cm) of the i-th tree of the plot; s is the area of the plot (0.09 ha).

Lorey's mean height (H_L, in meters), i.e. the mean height of all trees found in the plot, weighted by their basal area (Philip 2002), was calculated as follows:

$$H_L = \frac{\sum_{i=1}^{n} g_i h_i}{\sum_{i=1}^{n} g_i} \quad (9)$$

with

$$gi = \frac{\pi}{4} di^2 \quad (10)$$

The mean height of Lorey is more stable than an unweighted mean height, as it is less affected by mortality and registration of the smallest trees and is an important index for the dynamics of woody species (Glèlè Kakaï and Sinsin 2009).

Finally, the mean regeneration density was calculated for *K. senegalensis* following the formula:

$$Nr = \frac{1}{6}\sum_{i=1}^{6} d_{ri} \quad (11)$$

with

$$d_{ri} = \frac{ni}{sp} \quad (12)$$

The diameter class structures of all tree stand and populations of *K. senegalensis* in particular were analyzed: all trees were grouped into diameter classes of 5 cm in amplitude in order to obtain enough diameter classes to allow the adjustment of the theoretical distribution to the observed distribution. The observed diameter structure was fitted to 3-parameter Weibull with the following density function:

$$f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} exp\left[-\left(\frac{x-a^c}{b}\right)\right] \quad (13)$$

Where x = tree diameter; a = 5 cm, the tree diameter threshold for the forest inventory; a = scale parameter linked to the central value of the diameters; and c = shape parameter of the structure, which gives a good indication of the structure of the population and the potential dynamics (Glèlè Kakaï et al. 2016).

RESULTS

Floristic composition of Khaya senegalensis habitats

The multidimensional scaling showed two vegetation groups (G1 and G2). Group G1 was composed of a mixture of species belonging to the Sudano-guinean and Sudanian phytogeographical zones. It was found that these phytogeographical zones share a lot of the same species. However, the G2 group was mostly composed of species from the Sudano-sahelian zone (Fig. 3). Globally, 11 biological types and 14 phytogeographical types, 61 families, 178 genus and 300 plant species were identified in *K. senegalensis* habitats in Chad. According to the number of plant species (≥ 10 species), *Fabaceae*, *Poaceae* and *Rubiaceae* were dominated in Sudano-guinean phytogeographical zone (Fig. 4). These families accounted each respectively 35, 14 and 10 plant species. Moreover, *Fabaceae*, *Poaceae*, *Meliaceae* and *Euphorbiaceae* were the families with high area cover (Fig. 5).

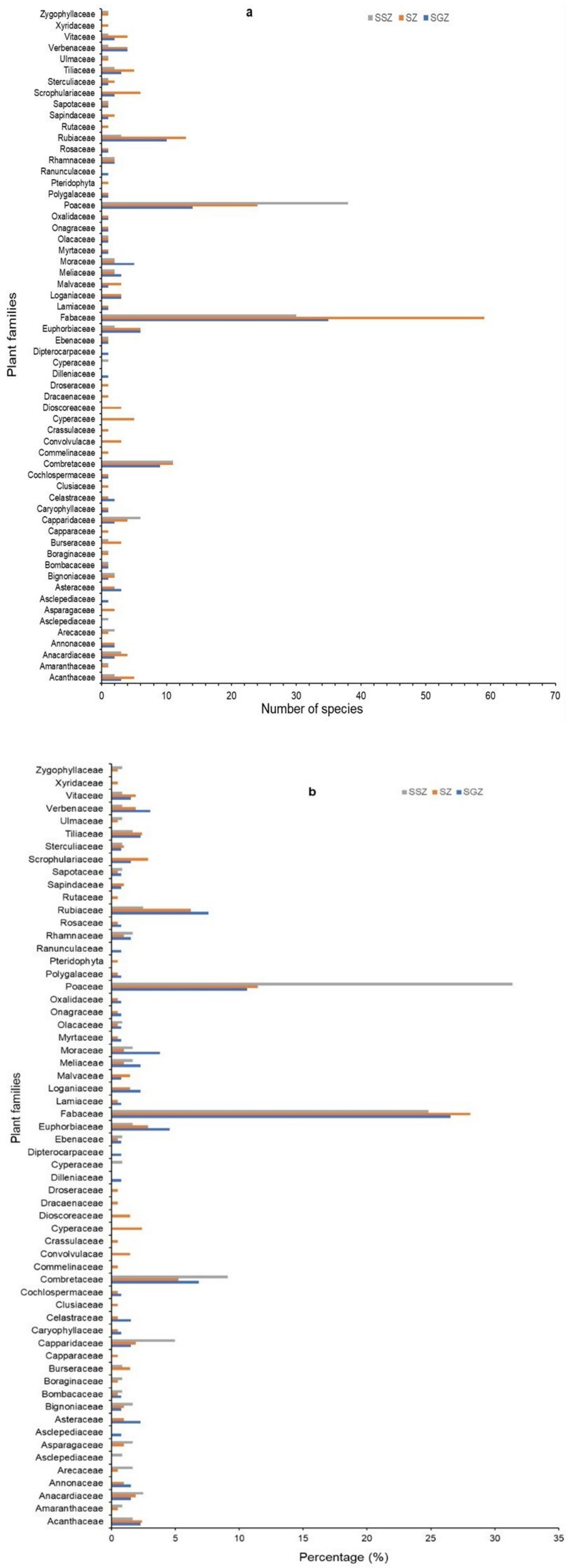

Fig.3 Spectrum of the biological families in the three climatic zones: SGZ = Sudano-Guinean Zone, SZ = Sudanian zone, SSZ = Sudano-Sahelian Zone, (a = raw value, b = weighted value)

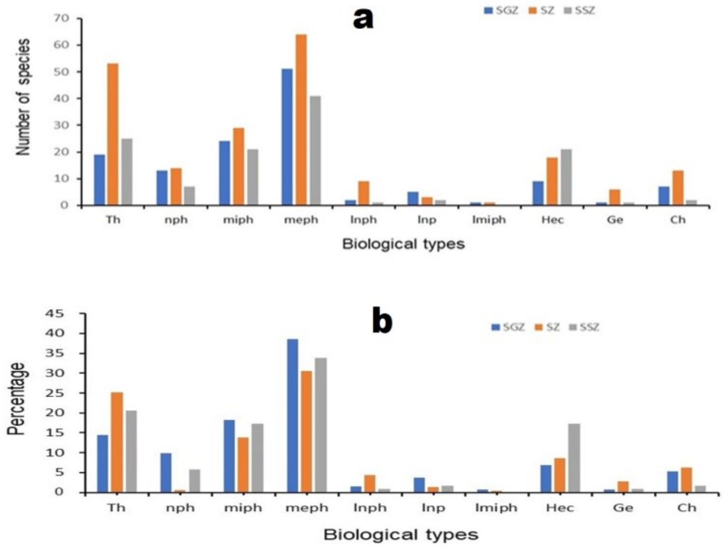

Fig.4 Spectrum of biologicals types in the three climatic zones:
SGZ = Sudano-Guinean Zone, SZ = Sudanian zone, SSZ = Sudano-Sahelian Zone
(a = raw value, b = weighted value)

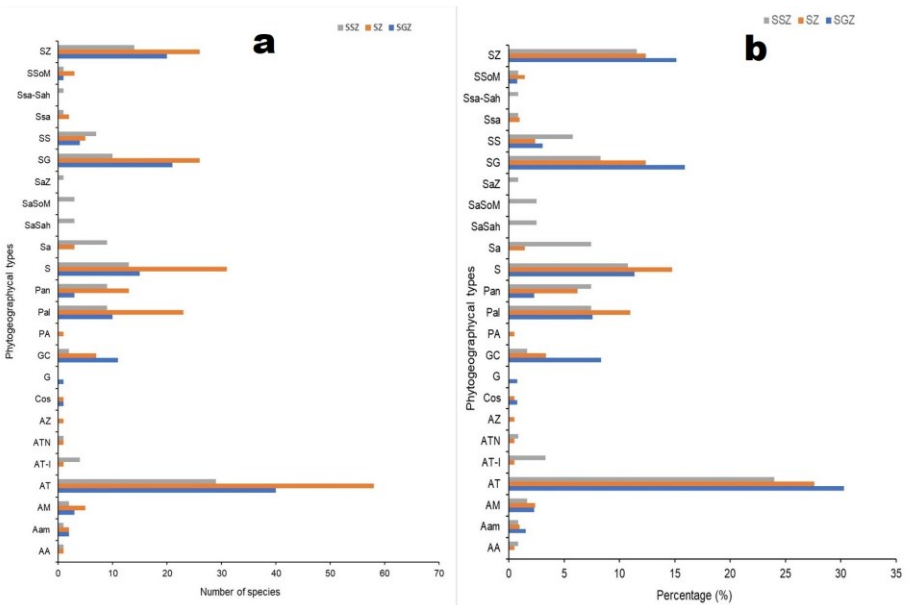

Fig.5 Spectrum of phytogeographic types in the three climatic zones:
SGZ = Sudano-Guinean Zone, SZ = Sudanian zone, SSZ = Sudano-Sahelian Zone
(a = raw value, b = weighted value)

In Sudanian phytogeographical zone, *Combretaceae* was added to *Fabaceae*, *Poaceae* and *Rubiaceae* as the dominated families in terms of the number of plant species (Fig. 4). Therefore, 59 species, 24 species, 13 species and 11 species were respectively attributed to these families. According to the area cover, the family of *Poaceae*, *Combretaceae*, *Fabaceae*, *Annonaceae* and *Meliaceae* were dominated in this phytogeographical zone (Fig. 4). However, in Sudano-sahelian phytogeographical zone *Poaceae* (38 species), *Fabaceae* (30 species) and *Combretaceae* (11 species) were dominated in terms of both plant species and area cover in the habitats (Fig. 4 and 5).

The three phytogeographical zones were dominated by Mesophanerophytes (Meph) (Fig. 6). In Sudano-guinean zone, Mesophanerophytes (Meph, 51 species) were followed by Therophytes (Th, 24 species), Microphanerophytes (Miph, 19 species) and Nanophanerophytes (Nph, 13 species) while in the Sudanian zone, Mesophanerophytes (Meph, 64 species) were followed by Therophytes (Th, 53 species), Microphanerophytes (Miph, 29 species), Hemicryptophytes (Hec, 18 species), Nanophanerophytes (Nph, 14 species) and Chamephytes (Ch, 13 species)

(Fig. 6). Moreover, Hemicriptophytes and Therophytes showed the best area cover after Mesophanerophytes (Fig. 7). However, Sudano-sahelian zone was dominated by Mesophanerophytes (Meph, 41 species), Therophytes (Th, 25 species), (Microphanerophytes (Miph, 21 species) and Hemicryptophytes (Hec, 21 species) (Fig.6).

According to phytogeographic spectrum (Fig.7), the vegetation of the three phytogeographical zones was dominated by Afro-tropical (AT) species with 40 species in Sudano-guinean zone, 58 species in Sudanian zone and 29 species in Sudano-sahelian. However, some phytogeographical types species were scarce including Cosmopilites species, Afro-zambesian species, Afro-asiatique species, Sudano-sahelo saharian species etc. (Fig.7).

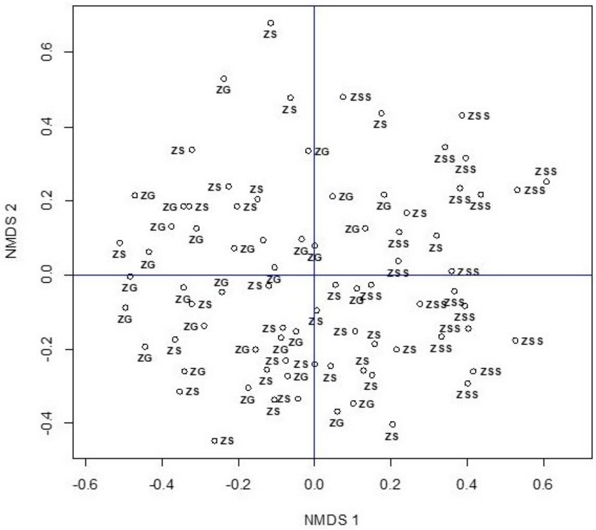

Fig.6 Projection of the three climatic zones in the system axes 1 and 2: SGZ = Sudano-Guinean Zone, SZ = Sudanian zone, SSZ = Sudano-Sahelian Zone

Floristic diversity of K. senegalensis habitats

The highest value of specific richness was obtained in Sudanian phytogeographical zone (203 species) and the lowest value (115 species) was found in Sudano-sahelian zone (Table 2). At the scale of each phytogeographical zone, a great species diversity was recorded with Shannon diversity index (H) values of 6.03 bits for Sudano-guinean zone, 7.06 bits for Sudanian zone and 6.85 bits for Sudano-sahelian zone. The index of Pielou's evenness varied between 0.88 and 0.92 for these zones (Table 2). In addition, the results also showed high similarity between phytogeographical zones of Sudano-guinean and Sudanian (Sorensen's similarity index was 94.2%) while a weak similarity was found between the previous zones and phytogeographical zones of Sudano-sahelian (Sorensen's similarity index was 6%).

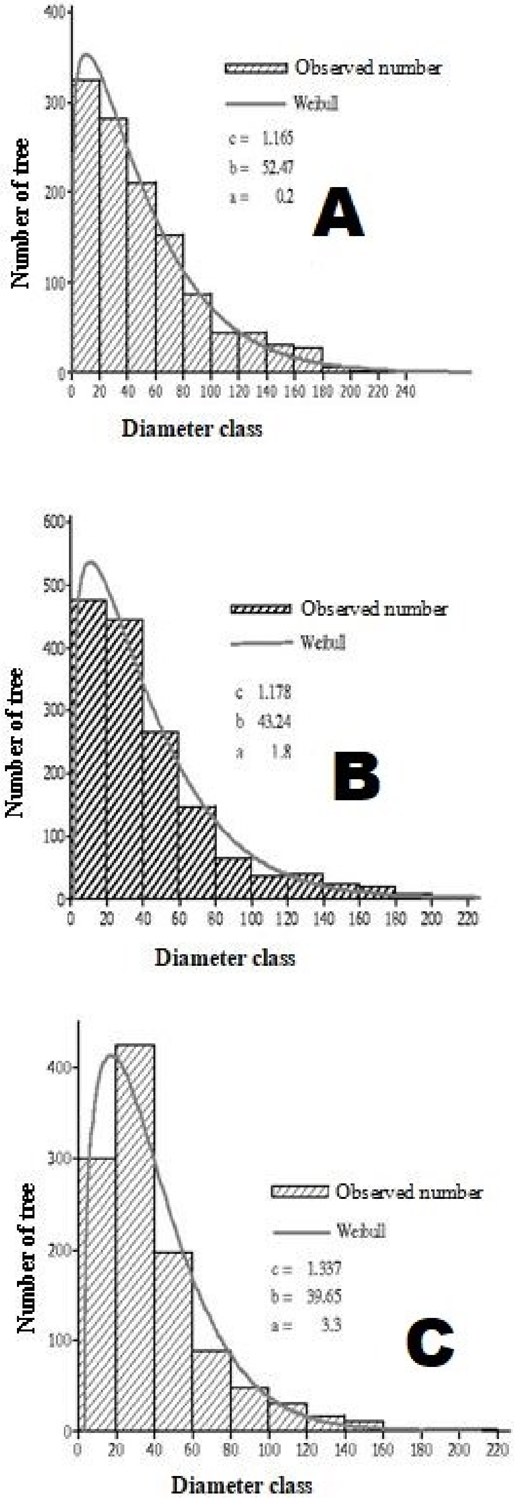

Fig.7 Diameter structure of measured tree individuals: A = Sudano-Guinean zone, B = Sudanian zone and C = Sudano-Sahelian zone

Table 2 Diversity index of species populations in the three climate zones studied

Phytogeographical zones	Species richness	Shannon's diversity	Pielou index
Sudano-Guinean	126	6.03	0.91
Sudanian	203	7.06	0.92
Sudano-Sahelian	115	6.85	0.88

Table 3 Dendrometric parameters of stands of all tree and K. Senegalensis species in the three Phytogeographical zones

Dendrometric parameters	Phytogeographical zones		
	Sudano-Guinean	Sudanian	Sudano-Sahelian
Mean density (N, tree/ha)	597.8	528	439.6
Basal area (G, m^2)	4612.1	4326.7	3874.9
K. Senegalensis			
Mean density (N, tree/ha)	272.2	347.8	387.5
Basal area (G, m^2)	2725.47	3176.33	2882.22

Dendrometric parameters of stands in K. senegalensis habitats

High population density, the largest basal area and full height have been observed in Sudano-guinean phytogeographical zone, while the Sudano-sahelian phytogeographical zone showed the lowest value of these parameters (Table 3). Regarding to the K. Senegalensis species, the results revealed that the species was more abundant in the Sudanian phytogeographical zone (3478 tree/ha) while the largest basal area was recorded in the Sudano-guinean phytogeographical zone (Table 3). The finding showed also that the density of species regeneration was high in the Sudano-guinean phytogeographical zone (Table 3). Moreover, the lowest values were still recorded for the Sudano-sahelian phytogeographical zone (Table 3).

Diametric and height stands structures in K. Senegalensis habitats

The structure of diameter classes revealed a positive asymmetric (Fig. 8). This observation meant that the small diameter has dominated the tree stands of K. Senegalensis habitats in the three phytogeographical zones. Moreover, it was notified the dominance of the diameter class [20, 40[in the phytogeographical zone of Sudano-sahelian zone (Fig. 7c).

With respect to the distribution by total height class, individuals in height classes [5, 10] and]10, 15] dominated the stands (Fig. 8). In the Sudano-Guinean zone, these height classes contained nearly 1/3 of the individuals in the stand. For the Sudanian and Sudano-Sahelian zones, the height classes [5, 10] contain more than 2/3 of the individuals in the stand.

The diametric distribution of K. senegalensis is positively asymmetric with a J shape reversed by the dominance of the lower diameter classes in Sudano-Guinean zone (Fig. 8a) and the Sudanian zone (Fig. 8b). In Sudano-Sahelian zone, this distribution tends mostly to be normal (Fig. 9c). However, in the Sudano-Guinean zone, there was a drastic individual reduction in the diameter class of [20, 40].

For the total height distribution, the individual classes show different structures between the three climatic zones. Thereby, a high individual number was recorded in the upper classes [20, 25] and]25, 30] as well as in the lower classes [0, 5],]5, 10] and]10, 15] in Guinean zone (Fig. 8a). The Sudanian zone revealed a structure showing a high number of individuals in the smaller size classes. (Fig. 10b). With regard to the Sudano-Sahelian transition zone, the distribution is very close to normal with the majority of individuals of the species in the middle classes]5, 10],]10, 15] and]15, 20] (Fig. 10c).

DISCUSSION

Floristic studies have shown that *Fabaceae*, *Combretaceae* and *Meliaceae* have always been among the top five families most represented in each climate zone. This may be due to the fact that *Combretaceae* and *Fabaceae* are abundant in savannahs and some wet dense forests in Africa (Thiombiano 2005).

Mesophanerophytes were the most abundant biological types in the three climatic zones. Mesophanerophytes were followed by microphanerophytes (miph) and nanophanerophytes (nph) in the Guinean zone, therophytes (Th) and microphanerophytes (miph) in the Sudanian and Sudano-Sahelian zones. According to Sinsin (1993) and Melom et al (2015), biological types provide information on the origin, transformation and type of plant formations. The arborescent structure of the vegetations in these zones is likely due to the predominance of mesophanerophytes in the stands. Indeed, the abundance of mesophanerophytes and microphanerophytes indicates good ecological conditions within these savannahs' formations and woodlands. The observed microphanerophytes are in fact the phanerophytes represented by shrubs of 2 to 10 m high.

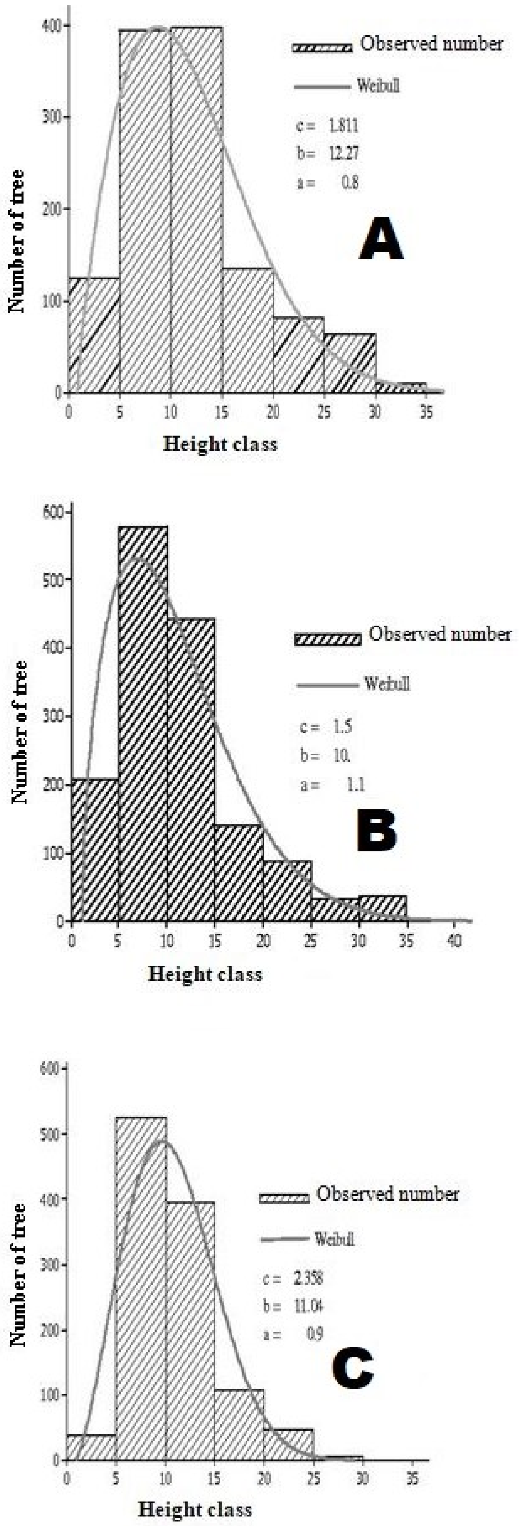

Fig.8 Height structure of measured tree individuals: A = Sudano-Guinean zone, B = Sudanian zone and C = Sudano-Sahelian zone

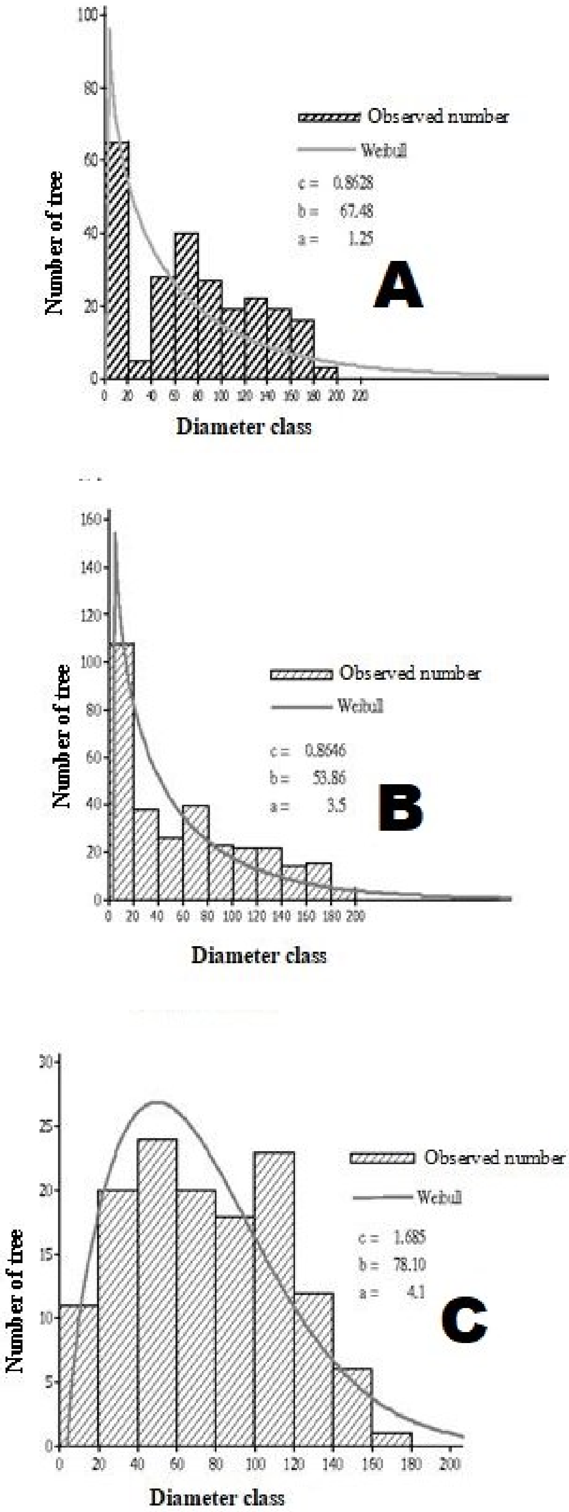

Fig.9 Diameter structure of individuals of Khaya senegaleensis: A = Sudano-Guinean zone, B = Sudanian zone and C = Sudano-Sahelian zone

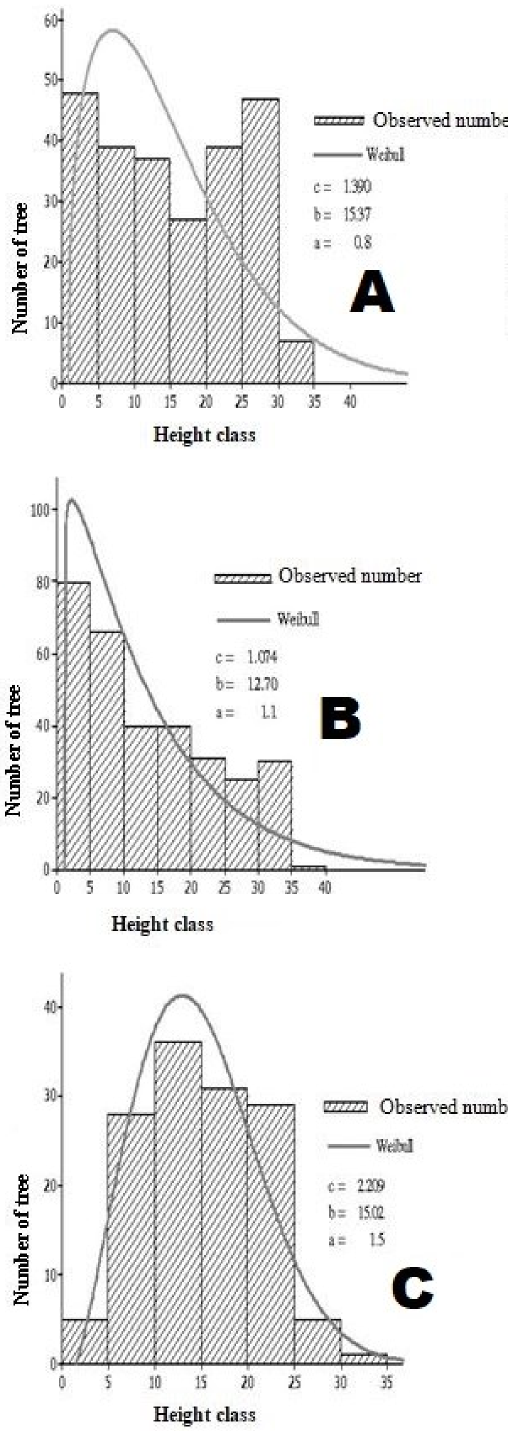

Fig.10 Height structure of individuals of Khaya senegaleensis: A = Sudano-Guinean zone, B = Sudanian zone and C = Sudano-Sahelian zone

Phytogeographic types are good indicators of the dynamism or stability of plant communities (Sinsin 1993). In the study areas, the preponderance of Afro-tropical, Sudano-Guinean and Sudano-Zambezian species was noted over the other phytogeographical types. This result shows that the climatic zones have not yet lost their phytogeographical specificities. The high proportion of these species is an indicator of the fidelity to their confining zone. In addition, this result is characteristic of woodlands and Sudanian savannahs (Pallo and Sawadogo 2010; Adomou 2005). Similar results have been found by Nguinambaye et al. (2015) who revealed a dominance of these phytogeographic types in central and northern Chad.

The species richness is higher in the Sudanian zone and lower in the Sudano-Sahelian zone. However, within each climatic zone, a great diversity of accompanied species with good regularity have been recorded. This shows the equiprobability of different species and the importance of their habitats in the conservation of biological diversity. The results also indicated that *K. senegalensis* is the species with the highest importance value index (IVI) in the three climatic zones. This would probably be due to the fact that all parameters were measured at the distribution and abundance areas of *K. senegalensis*. In the Guinean zone, *Daniellia oliveri*, *Vitellaria paradoxa*, *Parkia biglobosa* and *Prosopis africana* respectively come after *K. senegalensis*. In the Sudanian zone, *Daniellia olivera*, *Anogeissus leiocarpus*, species of the genus Combretum (especially *Combretum glutinosum*) and *Vitellaria paradoxa* follow in the footsteps of *K. senegalensis*. In the Sudano-Sahelian zone, *K. senegalensis* is followed respectively by *Balanites aegyptiaca*, species of the genus Acacia (*A. seyal*, *A. nilotica* and *A. sieberiana*) and *Piliostigma reticulatum*. These results are consistent with those obtained in the same zones by Gillet (1963), Pias (1970), Thomassey (1991), Bechir and Kabore-Zoungrana (2012), Nguinambaye et al. (2015) and Mbaiyetom et al. (2020). These species determine the vegetation physiognomy in each zone. The relative importance of Acacia and other thorn plants such as *Balanites aegyptiaca* and *Piliostigma reticulatum* in the Sudano-Sahelian zone indicates the Sahelian character of the vegetation of this zone and this is confirmed by the results of the NMDS analysis.

The results related to the vegetation composition showed two distinct groups. The first group consists mainly of Sudano-Guinean zone (SGZ) and Sudanian zone (SZ) species. The second group is mainly constituted by species from the Sudano-Sahelian zone (SSZ) accompanied by some Sudanian species. The similarity between the vegetations of Sudano-Guinean zone and Sudanian zone shows the climatic similarity between the two areas in Chad. White (1986) showed that the Sudano-Guinean and Sudanian climatic zones in Chad are included in the same regional endemism centre. Thereby, a tropical climate with summer rains reign, and the rainfall varies between 900-1300 mm/year. These results also corroborate the findings of Gillet (1963) and Pias (1970) and were confirmed by beta diversity close to zero (= 6%) between the Sudano-Guinean and Sudanian zones. The work of Nguinambaye et al. (2015) also showed that the Sudano-Guinean and Sudanian zones in Chad consist essentially of the same type of vegetation represented by treed savannahs and woodlands. With a beta diversity index of 48% between the Sudanian and Sudano-Sahelian zones, the floristic composition of the Sudano-Sahelian zone seems more dissimilar from the Sudano-Guinean zone. The floristic composition of the vegetation in Sudano-Sahelian zone seems closer to the one of Sahelian zone which is characterized by arid species. These results corroborate the findings of Bechir and Kabore-Zoungrana (2012) on woody forages in savannah areas in Chad.

The highest overall density average of stands was observed in the Sudano-Guinean zone with 449 trees/ha while the largest basal area (37.35 m^2/ha) was observed in the Sudano-Sahelian zone. The result of the basal area could be explained by the low density in the zone and stands are dominated by trees of higher diameters. The density of *K. senegalensis* was higher in the Sudanian zone than in the Sudano-Sahelian zone. The highest density of the plant population observed in the Sudano-Guinean zone is explained by the relatively mild ecological conditions allowing the zone's vegetation to flourish with less difficulty. Indeed, this zone is the only area of the country where the unimodal rainy season lasts at least 5 months (May to October) with rainfall exceeding 1200 mm/year. The high density of *K. Senegalensis* in the relatively drier zones reflects the climate preference of the species. Biogeographically, *K. senegalensis* is a naturally occurring species that grows in dry areas of Africa, particularly in the Sudanian and Sudano-Sahelian areas where average annual rainfall is lower (Soha et al. 2019). It occurs more in woody savannah, in areas with 650–1,300 (–1,800) mm of annual rainfall and can tolerate a 4–7 month dry season (Ouinsavi 2000; Soha et al. 2019). When the drought becomes longer (>7 months), this influences the density of *K. senegalensis* populations. This could justify the low density of the species in the Sudano-Sahelian transition zone.

The regeneration density of *K. senegalensis* is higher in the Sudano-Guinean zone (368 plants/ha) and lower in the Sudano-Sahelian zone (40 plants/ha). This gives evidence to the influence of climatic factors on the species. The low rainfall of the Sudano-Sahelian zone could negatively influence the germination capacity of *K. senegalensis* seeds. Indeed, seeds from the Sudano-Guinean zone ripen without too much difficulty and their germinative power is relatively high in contrast to seeds from the Sudano-Sahelian or Sudanian zone that quickly enter dormancy because of the low water content (Akabassi et al 2020).

In the different climatic zones, tree individuals of small diameter largely dominated the stands. Thereby, very low tree numbers were observed in the large diameter classes. The scarcity of large-diameter individuals indicates human pressure on these subjects. It could be the consequence of uncontrolled exploitation of local people. In Chad, *K. senegalensis* suffer of the uncontrolled harvesting of bark, leaves, seeds, roots and also widely exploited as lumber (Issa et al. 2018). The various species uses pose a major threat to the survival of large-diameter individuals. Moreover, the relative dominance of medium and small diameters, can also attest to the vitality of the stands but also be the result of the drastic measure taken by the authorities for more than 10 years prohibiting all cutting of green wood and carbonization over the entire national territory.

CONCLUSION

The structure and ecology of *Khaya senegalensis* vegetation in Chad revealed that the three climate zones are made up of 300 plant species included 66 families, 178 genera, 11 biological types and 14 phytogeographical types. *K. senegalensis* had the highest Value Index of Importance across the three climate zones. Analysis of diameter class structures revealed a preponderance of young or small-diameter individuals. The vegetation of the Sudano-Guinean (SGZ) and Sudanian (SZ) zones has similar floristic and dendrometric structures. The Sudano-Guinean zone has a high tree density compared to other climate zones. The results of this study are fundamental for the conservation and sustainable management of *K. senegalensis* and its habitats in Chad. In addition, the findings add knowledge to the species conservation. However, the methodological limitations related to sampling should not be obscured. Therefore, the species areas of abundance were randomly identified while plots were placed stratified.

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