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Ecological characteristics of the woody stand of *Sclerocarya birrea* (A. Rich) in the North of Ferlo, Senegal

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Abstract
The Ferlo, a semi-arid Sahelian region of Senegal, experiences intense heat for five months (February to June), with temperatures exceeding 45°C, and a milder climate for seven months (July to January) thanks to rainfall. This area is being heavily impacted by climate change. Low rainfall, combined with human activities, is affecting the development of plant cover, particularly woody species, which are essential to the local population as a source of food for livestock during the dry season. This study aims to characterize the structure, diversity and dynamics of a woody stand of *Sclerocarya birrea* in Ferlo (Amaly, Widou Thiengoly, Tessékéré and Labgar). It focuses on the dendrometric characteristics of this species as well as the floristic composition and regeneration of the stand, to provide essential data for the conservation of biodiversity and the improvement of sustainable management and ecological restoration strategies. We counted 31 species in 23 genera and 15 families, with the Fabaceae (25.81%), *Combretaceae* (19.35%), *Apocynaceae* (12.90%) and *Malvaceae* (6.45%) being the most represented. The genus *Acacia* is the most common. Almost all the species observed are Phanerophytes and around 68% of the species recorded are African. The study shows that the shrub stratum dominates the environment, while the woody stratum is gradually evolving, with a strong presence of young individuals and good regeneration. However, the population of *S. birrea* is following an opposite dynamic, with mainly large-circumference individuals, indicating an ageing and vulnerable population. The analysis reveals instability in the *S. birrea* population and almost no regeneration. It is therefore essential to develop regeneration, reforestation and monitoring strategies to improve the conservation of biodiversity and ecosystem services.

Keywords: *S. birrea*, Ferlo, Senegal, Timber, Structure, Distribution

Introduction

In the Sahelian region of Senegal, particularly in the Ferlo, the combination of the adverse effects of climate change and anthropogenic pressure has led to significant degradation of this agro-ecological zone. Rainfall has become less abundant and more irregular, while the intensive use of wood as fodder is emblematic of human pressures on the environment [33]. The growing demand for agricultural land, the constant increase in livestock numbers and inadequate management practices have considerably reduced the density of trees and shrubs [43].

To counter this degradation, several initiatives have been launched, including the Great Green Wall (GGW) project, a pan-African project aimed at curbing the expansion of the desert [30]. This project promotes the reintroduction of local forest species with multiple uses and socio-economic interest [41]. In Senegal, species such as *Acacia senegal* (L.), *Acacia raddiana* (Savi.), *Sclerocarya birrea*, *Faidherbia albida* (Del.), *Balanites aegyptiaca* (L.) Del. And *Ziziphus mauritiana* Lam. are priorities for planting programs.

The success of these strategies depends on the implementation of sustainable management to restore the protective role of trees on sensitive soils. This requires an in-depth understanding of plant dynamics, biodiversity conservation and ecosystem restoration processes. Unfortunately, the lack of scientific data limits the precise assessment of conservation priorities, thus hindering the application of effective planning practices and sustainable management of biodiversity [27].

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This study fits into this context by focusing on the dendrometry characteristics of a *S. birrea* woody stand. Its aim is to contribute to better conservation of biodiversity and ecosystem services in the Ferlo, by providing crucial information to guide sustainable management and ecological restoration strategies.

Material and Method

1. Sampling plan

The study was conducted based on previous research by [29] and [42], who confirmed the presence of the species in the selected sites. Random sampling was carried out using two main axes as reference (Fig. 1):

- West (W) - East (E) axis: Covering Widou Thiengoly, Tessékéré and Labgar.
- North (N) - South (S) axis: Covering Widou Thiengoly and Amaly.

A total of 44 surveys were carried out along the Widou-Labgar axis and 20 surveys along the Amaly-Widou axis. The difference in the number of surveys between the two axes is justified by the variations in the density of the species observed in these regions.

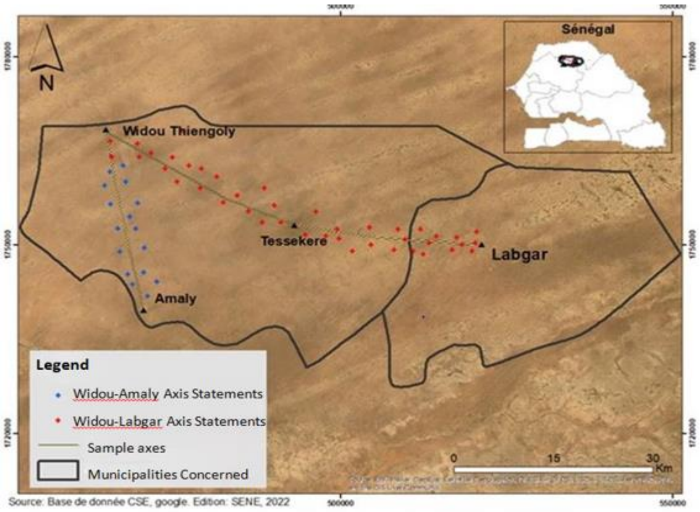

Figure 1. Random sampling

2. Vegetation survey method

Woody vegetation was sampled using a dendrometric approach over a minimum area of 2500 m², following the recommendations of [9] for Sahelian zones. In each plot, woody plants with a base circumference ≥ 10 cm at 30 cm from the ground were identified and measured, considering the multicaulus trees common in the Ferlo region, unlike the diameter at breast height (DBH, measured at 1.30 m). The total height of the trees was measured with a Blume-Leiss and the crown with a 50 m tape. The regeneration of the species, including individuals with a circumference of less than 10 cm, was also assessed [10].

Figure 2. Dendrometric measurements

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3. Data processing

3.1. Floristic list

The scientific names of the species were transcribed and updated using specialist manuals and the Iplant Collaborative tool [8, 7, 3]. The botanical families follow the APG III classification, and the chorological spectrum is based on the Lebrun and Stork classification [26]. The floristic list is organized by taxonomic group and the abbreviations for the phytogeographical affinity of the species are: gu (Guinean), so (Sudanian), sa (Sahelian), sa so (Sahelo-Sudanian), so gu (Sudano-Guinean), so sa (Sudano-Sahelian), gu so (Guineo-Sudanian).

3.2. Floristic diversity

Floristic diversity assesses the variability of plant species, including floristic richness (total number of species) and regularity (distribution of individuals). The Shannon-Weaver and Pielou indices are used to measure this. The Shannon-Weaver index (H') takes account of species abundance and varies from 0 to around 4.5 for a rich community:

$$H' = -\sum_{i=1}^{S} \left(\frac{Ni}{N}\right) * \log 2 \frac{Ni}{N}$$

The Pielou equitability index (E) normalizes H' on a scale of 0 to 1[18], where E is maximum when all species are equally abundant:

$$E = \frac{H'}{Hmax} = \frac{H'}{Log2S}$$

This represents the maximum diversity considering the total number of species (S).

3.3. Vegetation indices

Vegetation indices provide information on the structure and dynamics of a plant stand. The main indices are:

Relative density (ReD): Proportion of the number of individuals of a species in relation to the total number of individuals:

$$ReD = \frac{Ni}{N} * 100$$

Relative dominance (RoD): Proportion of specific basal areas in relation to total basal area:

$$RoD = \frac{Ste}{St} * 100$$

Importance Value Index (IVI): Combines relative density, relative dominance and relative frequency (FR) [13, 10] quoted by [25]: $IVI = RF + RoD + ReD$

Relative frequency (RF): Proportion of the centesimal frequency (Cf) in relation to the sum of the specific frequencies (F):

$$\text{Relative frequency (RF)} = \frac{Cf}{F} * 100$$

Frequency of presence (Fp): Proportion of records where the species is present:

$$Fp = \frac{\text{Number of records in which the species is present}}{\text{Total number of records}} * 100$$

3.4. Structure of woody vegetation

3.4.1. Actual density, basal area, aerial cover and regeneration

Actual density: Number of individuals per hectare [39]:

$$\text{Density} = \frac{\text{Number of individuals (circumference} > 10)}{\text{Sampled area (ha)}}$$

Basal area (Ba): Sum of basal areas of individuals (circumference > 0.30 m) [40] ; [46]:

$$Ba = \frac{\frac{\sum C^2}{4\pi}}{SE}$$

where (C) is the circumference at 0.30 m from the ground of the tree considered.

Aerial cover (Ac): Crown area per hectare:

$$Sc = \frac{\sum \pi D^2}{4} / SE$$

Where (D) is the average crown diameter (measured East/West and North/South).

Regeneration:

Regeneration rate (Rr): Ratio between the number of young plants and the total number of individuals:

$$Rr = \frac{Nv}{Nv + Na} * 100$$

where Nv is the number of young plants and Na the total number of adult individuals.

Specific Importance of Regeneration (SIR): Proportion of seedlings of a species in relation to the total number of seedlings:

$$SIR = \frac{Ns}{\mathrm{Na}} * 100$$

where Ns is the number of seedlings of species (s) and Na is the total number of seedlings.

These measures characterize the structure, density, cover and regeneration of woody plant populations.

3.4.2. Horizontal and vertical structure of woody vegetation

Horizontal structure: Analyses the distribution of individuals and their spatial occupation in the horizontal plane [23]. It assesses the abundance, dominance and relative frequency of trees per unit area.

Vertical structure: Evaluates the distribution of individuals according to their height.

Trees: Individuals with height ≥ 7 m.

Shrubs: Individuals with height < 7 m.

These two components are used to characterize the spatial distribution and height stratification of woody plant stands.

4. Statistical processing of data

The field data were analyzed using Excel to classify the data and create graphs. Vegetation parameters such as floristic composition, diversity, spatial distribution, density, basal area and cover were calculated.

For the specific study of *S. birrea*, Minitab 17 was used to analyze circumference and height structures. The Weibull distribution applied by [22], with its parameters a, b and c, was applied to model the height structure of the *S. birrea* population.

This distribution is based on the probability density function defined by [39] and takes the following form: F (x) = c/b [(x-a) /b] c-1 expo [- [(x-a) /b] c], Où.

Results and Discussion

1.1. Richness and importance of the flora

The overall list of species and families inventoried is presented in Table 1. This table provides detailed information on the diversity of taxa within each family, with the number of genera and species. Each species is associated with its biological type (BT), biogeographical distribution (BD) and phytogeographical affinity (PA).

A total of 31 species were identified, divided into 23 genera and 15 families. The most represented families in terms of number of species are the *Fabaceae* (comprising the subfamilies *Faboideae, Caesalpinioideae* and *Mimosoideae)* with 8 species, followed by the *Combretaceae* with 6 species, the*Apocynaceae*with 4 species and the *Malvaceae*with 2 species. The other families present include only one species each, namely: *Anacardiaceae, Arecaceae, Bignoniaceae, Burseraceae, Capparaceae, Celastraceae, Euphorbiaceae, Myrtaceae, Menispermaceae, Rubiaceae, Rhamnaceae, Sterculiaceae et Zygophyllaceae.* The most represented genera are *Acacia* and *Combretum*, with 5 and 3 species respectively.

Table 1. **List of woody species**

Families	Subfamilies	NG	NS	Species	BT	BD	PA
Anacardiaceae		1	1	*Sclerocarya birrea* (A. Rich.) Hochst.	Phanerophyte	Af	sa so
Apocynaceae	*Asclepioidae*	3	4	*Calotropis procera* (Aiton) W. T. Aiton	Phanerophyte	As	sa
				Adenium obesum (Forssk.) Roem. & Schult. Phanérophyte		As	so sa
				Leptadenia lanceolata (Poir.) Goyder	Phanerophyte	Af	so
				Leptadenia pyrotechnica (Forssk.) Decne.	Phanerophyte	Cosm	sa so
Bignoniaceae		1	1	*Stereospermum kunthianum* Cham.	Phanerophyte	Af	sa so

Burseraceae		1	1	*Commiphora africana* (A. Rich.) Engl.	Phanerophyte	Af	sa
Celastraceae		1	1	*Maytenus senegalensis* (Lam.) Exell	Phanerophyte	Mase	so
Capparaceae		1	1	*Boscia senegalensis* (Pers.) Lam. Ex Poir.	Phanerophyte	Af	sa so
Combretaceae		4	6	*Anogeissus leiocarpa* (DC.) Guill. & Perr	Phanerophyte	Af	sa so
				Combretum aculeatum Vent.	Phanerophyte	As	sa so
				Combretum glutinosum Perr. ex DC	Phanerophyte	Af	sa so
				Combretum micrantum G.Don	Phanerophyte	Af	So
				Terminalia avicennioides Guill. & Perr.	Phanerophyte	Af	So
				Guiera senegalensis Lam.	Phanerophyte	Af	sa so
Euphorbiaceae		1	1	*Jatropha chevalieri Beille*	Phanerophyte	Af	so sa
Fabaceae	*Caesalpinoidae*	4	2	*Bauhinia rufescens* Lam.	Phanerophyte	Af	sa so
				Piliostigma reticulatum (DC.) Hochst.	Phanerophyte	Af	so sa
	Faboidae		1	*Dalbergia melanoxylon* Guill. et Perrott.	Phanerophyte	As	sa so
	Mimosoidae		5	*Acacia pennata* (L.) Willd	Phanerophyte	As	sa so
				Acacia senegal (L.) Willd.	Phanerophyte	Mas	sa
				Acacia ehrenbergiana Hayne	Phanerophyte	As	sa so
				Acacia seyal auct.	Phanerophyte	As	
				Acacia tortilis var. raddiana	Phanerophyte	As	sa so
Malvaceae	*Bombocoidae*	2	2	*Adansonia digitata* L.	Phanerophyte	Ma	so sa
	Tilicoidae			*Grewia bicolor* Juss.	Phanerophyte	Af	sa so
Menispermaceae		1	1	*Tinospora bakis* (A. Rich.) Miers	Geophyte	Af	sa so
Streculiaceae			1	*Sterculia setigera Delile*	Phanerophyte	Af	so
Rhamnaceae		1	1	*Ziziphus mauritiana* Lam.	Phanerophyte	As	so
Rubiaceae		1	1	*Feretia opodanthera* Del.	Phanerophyte	As	sa so

Zygophyllaceae	1	1	*Balanites aegyptiaca (*L.) Del	Phanerophyte	As	sa so
TOTAL	**24**	**31**				

African species (Af); Cosmopolitan species (Cosm); Afro-Asian species (As); Afro-Malagasy and Asian species (Mas); Afro-Malagasy species (Ma); Asian and European species (Mase). NG: Number of Genus N.S: Number of Species; sa so: Sahelo-Sudanian; so sa: Sudano-Sahelian; sa: Sahelian; so: Sudanian

1.2. Breakdown of species into families

The distribution of species by family and their percentage are shown in Table 2. Analysis of this table shows that the most represented family in our study area is the *Fabaceae,*with 4, see Table 1 genera and 8 species, representing 20.83% and 25.81% of the total respectively. It is followed by the *Combretaceae* family with 4, see Table 1 genera (12.50%) and 6 species (19.35%). The *Apocynaceae* and the*Malvaceae*families have 3 genera (12.50%) and 4 species (12.90%) respectively for the former, and 2 genera (8.33%) and 2 species (6.45%) for the latter. The other families have a lower distribution rate, with each family represented by one genus (4.17%) and one species (3.23%). These families include *Anacardiaceae*, *Bignoniaceae, Burseraceae*, *Sterculiaceae,Capparaceae*, *Euphorbiaceae*, *Celastraceae*, *Menispermaceae*, *Rhamnaceae*, *Rubiaceae* and *Zygophyllaceae.*

Table 2. Breakdown of species into families

Families	NG	Proportion (%)	NS	Proportion (%)
Fabaceae	4	16,67	8	25,81
Combretaceae	4	16,67	6	19,35
Apocynaceae	3	12,50	4	12,90
Malvaceae	2	8,33	2	6,45
Anacardiaceae	1	4,17	1	3,23
Bignognaceae	1	4,17	1	3,23
Burseraceae	1	4,17	1	3,23
Sterculiaceae	1	4,17	1	3,23
Capparceae	1	4,17	1	3,23
Euphorbiaceae	1	4,17	1	3,23
Celastraceae	1	4,17	1	3,23
Menispermaceae	1	4,17	1	3,23
Rhamnaceae	1	4,17	1	3,23
Rubiaceae	1	4,17	1	3,23
Zygophyllaceae	1	4,17	1	3,23
Total	**24**	**100**	**31**	**100**

1.3. Chorological spectrum

Geographical distribution of encountered species

The proportions of the geographical distribution of the species recorded are illustrated in Figure 3. Analysis of Figure 3 shows that most species present in the environment studied are African (As), representing 48.39% of the total, and Afro-Asian (Aa), with 38.71%. There are also intercontinental species with high ecological value and wide geographical distribution, notably cosmopolitan species (Cosm), Asian and European species (Mase), Afro-Malagasy species (Ma), and Afro-Malagasy and Asian species (Mas), each representing 3.23%.

This predominance of African species can be explained by the region's specific climatic and edaphic conditions, which favour species that are well adapted to arid and semi-arid environments. For example, Acacia senegal and Combretum micranthum are African species well known for their resilience to drought conditions. Intercontinental species, although less numerous, indicate a broad ecological range. Cosmopolitan species such as *Leptadenia pyrotechnica* can be found in a variety of environmental conditions, demonstrating a great capacity for adaptation.

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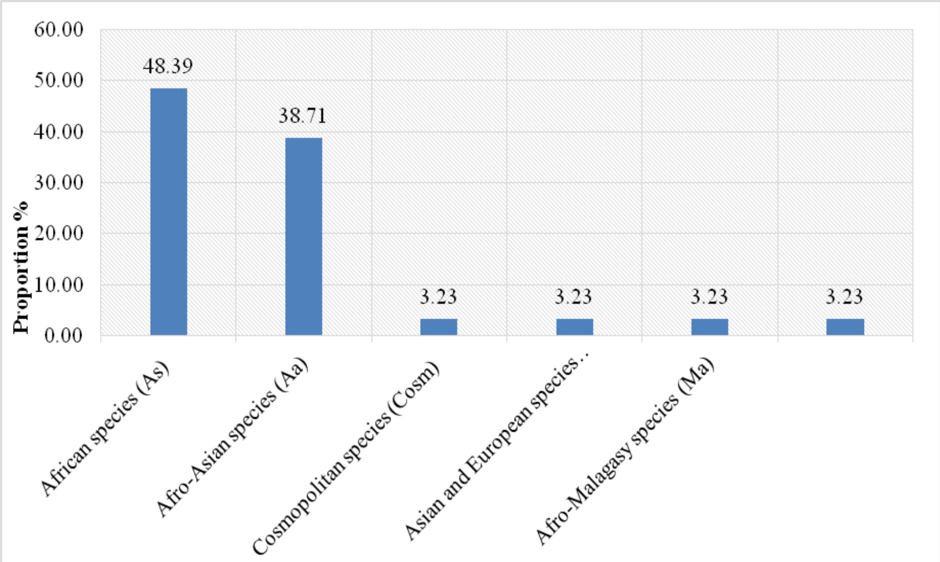

Figure 3. The proportions of species according to their geographical distribution

Phytogeographical affinities of the flora

Figure 4 shows the results obtained from the study of the phytogeographical affinities of the species recorded in the environment.

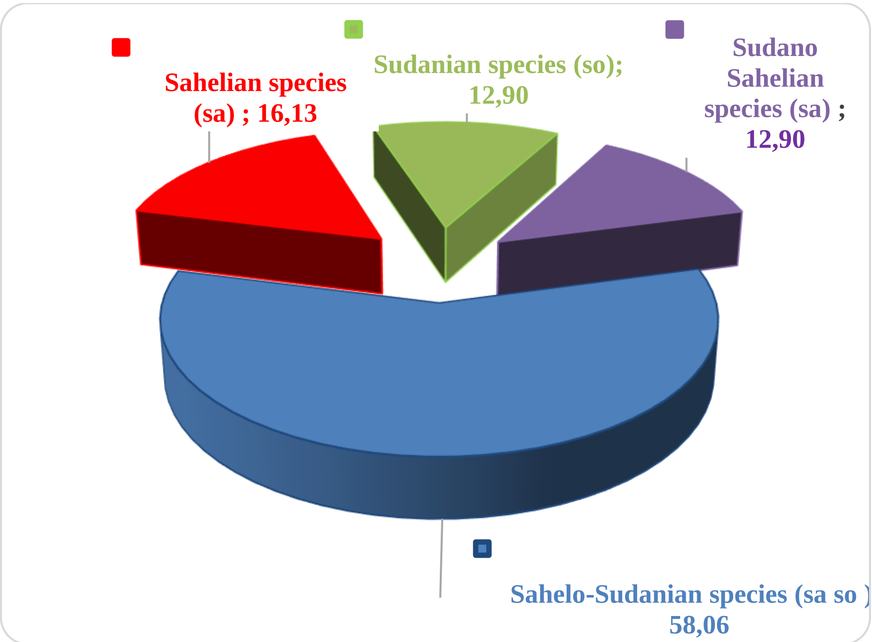

Figure 4. Proportion of species by phytogeographical affinities

Analysis of Figure 4 shows that the environment is dominated by Sahelo-Sudanian species (sa so), which account for 58.06% of the total, and Sahelian species (sa), which account for 16.13%. Species with Sudanian (so) and Sudano-Sahelian (so sa) affinities are less present, each accounting for 12.90% of the total.

This dominance can be attributed to the geographical position of the study area, located in a transition region between the Sahara and the Sudanian zone, favoring species adapted to marked seasonal variations in rainfall. Sahelian species (sa), representing 16.13%, reinforce the idea of a flora well adapted to arid conditions. Species such as *Balanites aegyptiaca* and *Ziziphus mauritiana* illustrate this adaptation.

Species with Sudanian (so) and Sudano-Sahelian (so sa) affinities, each representing 12.90%, indicate a certain ecological diversity in the environment, suggesting varied microhabitats and a mosaic of ecological conditions allowing different adaptive strategies to cohabit.

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1.4. Floristic diversity

1.4.1. Shannon - Weaver diversity index and Pielou equitability index

The biological diversity of the environment was assessed using the Shannon index and the Pielou equitability index. The values obtained for the Shannon index (2.54 bits) and the Pielou equitability index (0.51 bits) indicate that the environment is moderately diverse. The low value of the equitability index suggests the dominance of a few specific species in terms of representativeness, which may indicate an uneven distribution of species in the environment.

1.4.2. Relative density of each species (ReD)

In our environment, the most abundant species is *Calotropis procera*with a relative abundance of 33.17%, followed by *Balanites aegyptiaca* (25,09 %) and *Boscia senegalensis* (24,05 %). In contrast, species such as *Acaciapennata***,** *Adenium obesum***,** *Anogeissus leiocarpus***,** *Maytenus senegalensis***,** *Commiphora africana***,** *Dalbergia melanoxylon***,** *Leptadenia pyrotechnica***,** *Sterculia setigera* and *Terminalia avicennoides* had a low relative abundance of 0.06%. This indicates a limited presence of these species in the environment studied (Table 4).

1.5. Relative dominance of each species (RoD)

Analysis of Table 3 shows the dominant species in the woody stand of Ferlo Nord, Senegal. The main species such as *Adansonia digitata, Sclerocarya birrea* and *Boscia senegalensis* how significant proportions, with dominance indices of 22.79%, 21.40% and 18.15% respectively. In addition, *Balanites aegyptiaca, Acacia ehrenbergiana, Terminalia avicennoides, Guiera senegalensis* and *Acacia raddiana*had dominance indices of 12.38%, 6.03%, 3.47% and 2.35%.

1.6. Relative Frequency (RF)

The table 4 shows that *Sclerocarya birrea* records 54 occurrences, corresponding to a frequency of presence of 84.38% and a relative frequency of 21.69%. *Balanites aegyptiaca* and *Boscia senegalensis* come next with 43 and 36 occurrences, respectively, corresponding to frequencies of presence of 67.19% and 56.25% and relative frequencies of 17.27% and 14.46%. *Calotropis procera* presents 28 occurrences (FP = 43.75% and RF = 11.25%). Conversely, many species appear only once (FP = 1.56% and RF = 0.40%), indicating a very limited dispersion in the field. These values illustrate a strong disparity in the distribution of the species recorded.

Table 3. Frequency of occurrence (FP) and relative frequency (RF) of woody species surveyed

Species	Number of records/species	Frequency of presence (FP)	Relative frequency (RF)
Sclerocarya birrea	54	84,38	21,69
Balanites aegyptiaca (L.) Del.	43	67,19	17,27
Boscia senegalensis (Pers.)	36	56,25	14,46
Calotropis procera	28	43,75	11,25
Leptadenia hastata	15	23,44	6,02
Grewia bicolor	10	15,63	4,02
Acacia raddiana	9	14,06	3,61
Combretum glutinosum	9	14,06	3,61
Acacia senegal	8	12,50	3,21
Guiera senegalensis	6	9,38	2,41
Acacia seyal	4	6,25	1,61
Adansonia digitata	3	4,69	1,20
Feretia apodanthera	3	4,69	1,20
Jatropha chevaliri	3	4,69	1,20
Combretum aculeatum	2	3,13	0,80
Adenium obesum	1	1,56	0,40
Acacia ehrenbergiana	1	1,56	0,40
Acacia pennata	1	1,56	0,40
Anoseissus leiocarpus	1	1,56	0,40
Bauhinia rufescens	1	1,56	0,40
Combretum micrantum	1	1,56	0,40
Commiphora africana	1	1,56	0,40
Dalbergia melanoxylon	1	1,56	0,40
Leptadenia pyrotechnica	1	1,56	0,40
Maytenus senegalensis	1	1,56	0,40

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Piliostigma reticulatum	1	1,56	0,40
Pterocarpus licens	1	1,56	0,40
Stereospermum kunthianum	1	1,56	0,40

1.7. Importance Value Index (IVI)

The Importance Value Index (IVI), presented in Table 4, is used to assess the relative contribution of species to the overall structure of the woody stand.

Table 4. Species Importance Value Index

Species	Relative density (ReD)	Relative dominance (RoD)	Importance Value Index (IVI)
Boscia senegalensis	24,05	18,15	56,66
Balanites aegyptiaca	25,09	12,38	54,74
Calotropis procera	33,17	0,02	44,44
Sclerocarya birrea	6,24	21,4	49,33
Adansonia digitata	0,18	22,79	24,17
Leptadenia lanceolata	3,55	1,39	10,96
Acacia ehrenbergiana	0,43	6,03	6,86
Guiera senegalensis	0,92	2,45	5,78
Acacia raddiana	0,92	2,35	6,88
Grewia bicolor	0,73	1,11	5,86
Acacia senegal	0,61	0,54	4,36
Terminalia avicennoides	0,06	3,47	3,93
Combretum glutinosum	0,86	1,49	5,96
Acacia seyal	0,37	0,84	2,82
Jatropha chavalieri	1,22	0,64	3,06
Combretum micrantum	0,06	1,8	2,26
Ferethia apondantera	0,31	0,04	1,55
Bauhinia rufescens	0,06	1,25	1,71
Piliostigma reticulatum	0,06	0,8	1,26
Combretum aculeatum	0,18	0,02	1,00
Adenium obesum	0,06	0,61	1,07
Dalbergia melanoxilon	0,24	0,23	0,87
Anoseissus leiocarpus	0,06	0,09	0,55
Tinospora bakis	0,12	0	0,52
Ziziphus mauritiana	0,06	0,05	0,51
Acacia pennata	0,06	0,03	0,49
Stereospermum kunthianum	0,06	0,02	0,48
Sterculea setigera	0,06	0,01	56,66
Commiphora africana	0,06	0	54,74
Leptadenia pyrotechnica	0,06	0	44,44
Maytenus senegalensis	0,06	0	49,33

These results reveal that *Boscia senegalensis, Balanites aegyptiaca,* and *Calotropis procera*occupy the top positions in terms of Importance Value Index (IVI), together accounting for more than 155.83% of the overall index. This distribution highlights their crucial role in the structure and dynamics of the North Ferlo ecosystem.

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1.8. Structure of woody vegetation

The structural parameters of woody plants are listed below, including true density, basal area and aerial cover, as well as Shannon's diversity index, Pielou's equitability index and regeneration rate.

1.8.1. Real density

A total of 1634 individuals were recorded, corresponding to a density of 16 individuals per hectare.

1.8.2. Basal area and aerial cover

The basal area, calculated from the height at breast height (DBH), is 8.83 m²/ha in the overall stand. The dominant species are *Adansonia digitata* (2.01 m²/ha), *Sclerocarya birrea* (1.89 m²/ha), *Boscia senegalensis* (1.60 m²/ha) and *Balanites aegyptiaca* (1.09 m²/ha). The basal area and aerial cover values for the species are shown in Table 4.

Total aerial cover is 1550.01 m²/ha. *Balanites aegyptiaca*, *Sclerocarya birrea*, *Boscia senegalensis* and *Calotropis procera* together account for more than half of this area, with percentages of 37.87%, 10.16%, 7.73% and 22.39% respectively.

Table 4. Basal area and aerial cover of species

Species	Basal area	Aerial cover
Acacia nilotica	0,53	0,3361
Acacia pennata	0	0,0039
Acacia raddiana	0,21	5,2361
Acacia senegal	0,05	1,6484
Acacia seyal	0,07	1,1200
Adansonia digitata	2,01	2,0471
Adenium obesum	0,05	0,0071
Anoseissus leiocarpus	0,01	0,8884
Balanites aegyptiaca	1,09	37,8746
Bauhinia rufescens	0,11	0,1781
Boscia senegalensis	1,6	10,1632
Calotropis procera	0	7,7316
Combretum aculeatum	0	0,1277
Combretum glutinosm	0,13	2,6264
Combretum micrantum	0,16	0,2710
Commifora africana	0	0,0626
Dalbergia melanoxilon	0,02	0,2471
Feretia apodanthera	0	0,2271
Grewia bicolor	0,1	1,4103
Gueira senegalensis	0,22	1,7077
Jatropha chavalieri	0,06	0,4923
Leptadenia hastata	0,12	1,8381
Leptadenia pyrotechnica	0	0,0445
Maytenus senegalensis	0	0,0148
Piliostigma reticulatum	0,07	0,3361
Sclerocarya birrea	1,89	22,3889
Sterculea setigera	0	0,0871
Stereospermum kunthianum	0	0,2342
Terminalia avicennoides	0,31	0,3555
Tinospora bakis	0	0,1316
Ziziphus mauritiana	0	0,1639
Total	8,83	100,0000

1.8.3. Regeneration rate

The inventory of woody plants revealed 1,634 adult individuals and 1,147 young plants belonging to 15 species. Applying the formula for the regeneration rate of a stand, the environment has a regeneration potential of 41.24%.

1.8.4. Specific importance of regeneration

Analysis of Figure 5 shows that *Calotropis procera* (35.31%), *Boscia senegalensis* (20.31%), *Balanites aegyptiaca* (18.05%) and Leptadenia lanceolata (15.52%) are the four species that regenerate the most, accounting for around 89% of the offshoots observed. Species such as *Leptadenia pyrotechnica, Acacia raddiana, Acacia senegal* and *Sclerocarya birrea* show a regeneration rate of between 0.5% and 3%. On the other hand, the following species: *Acacia ehrenbergiana, Acacia pennata, Adansonia digitata, Adenium obesum, Anoseissus leiocarpus, Combretum aculeatum, Combretum glutinosum, Combretum micrantum, Commiphora africana, Ferethia apodanthera, Maytenus senegalensis, Piliostigma reticulatum, Sterculea setigera, Stereospermum kunthianum, Terminalia avicennoides, Tinospora bakis* and *Ziziphus mauritiana,* show no signs of significant regeneration.

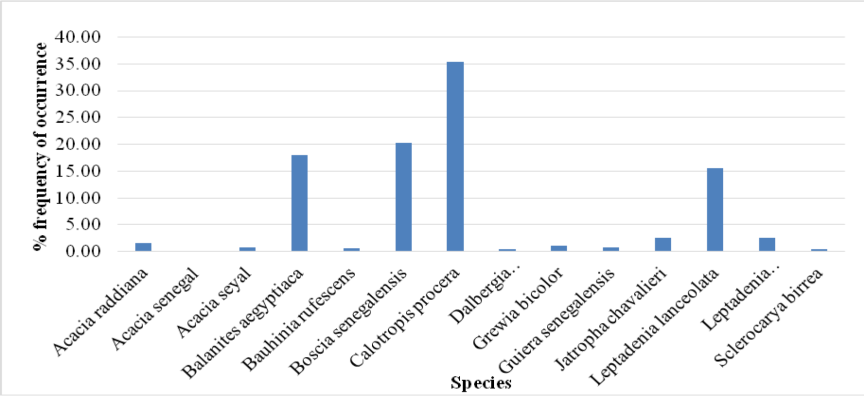
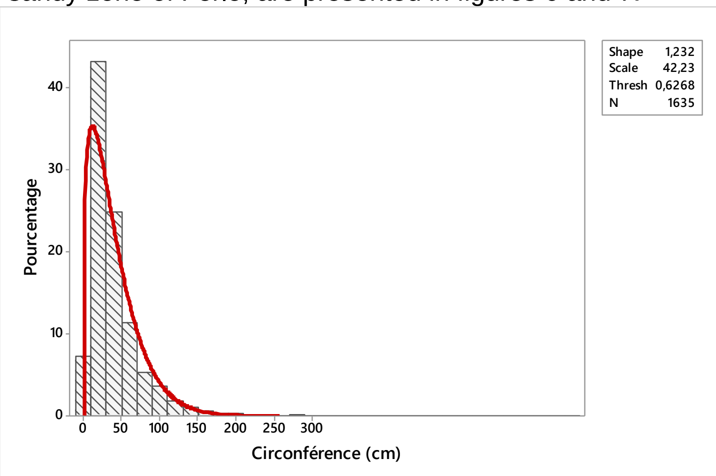


Figure 5. Specific regeneration importance (SRI)

1.9. Structure of woody vegetation

1.9.1. Horizontal structure of woody vegetation

The histograms of the circumference values of the trees in the woody stand and of *Sclerocarya birrea*, recorded in the northern sandy zone of Ferlo, are presented in figures 6 and 7.



Thresh (a) = position parameter; Scale (b) = scale parameter; Shape (c) = shape parameter of the Weibull distributio).

Figure 6. Distribution of individuals in the stand according to conferences

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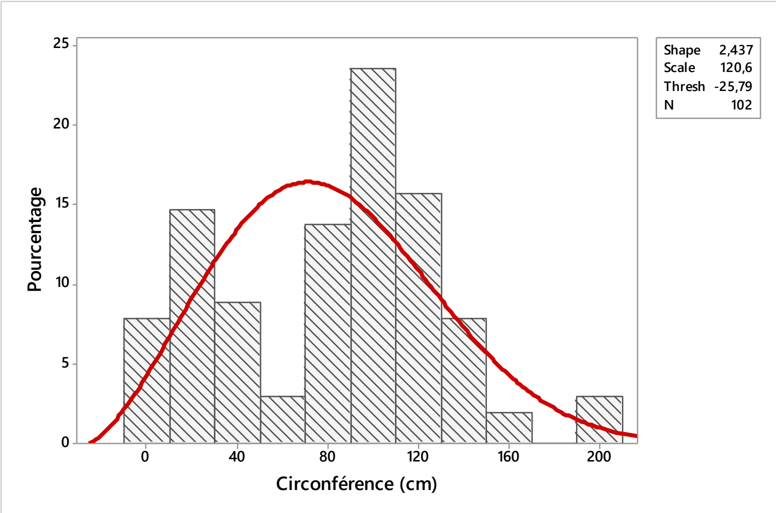
Analysis of the histogram (Figure 6) reveals a negative asymmetric distribution, also known as left asymmetry, with a shape parameter (c) equal to 1.232. This distribution indicates a relative predominance of young, small-circumference trees in the stand. Approximately 35% of the trees have diameters between 10 cm and 50 cm.



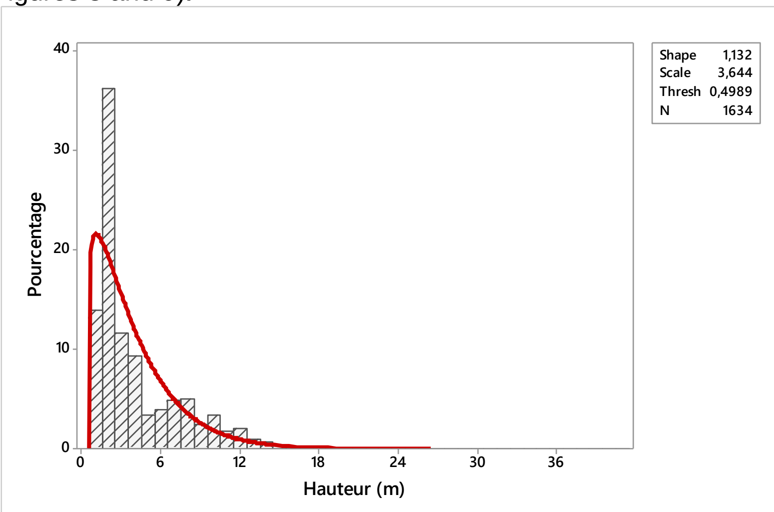
Thresh (a) = position parameter; Scale (b) = scale parameter; Shape (c) = shape parameter of the Weibull distribution.

Figure 7. Distribution of individuals in the *S. birrea* population according to circumference

The demographic structure of the *S. birrea* population, represented by the distribution of individuals according to circumference, shows a bell shape. The shape parameter (c) is equal to 2.437, indicating a more balanced distribution with a significant concentration of trees with circumferences between 80 cm and 120 cm.

1.9.2. Distribution des individus selon la hauteur

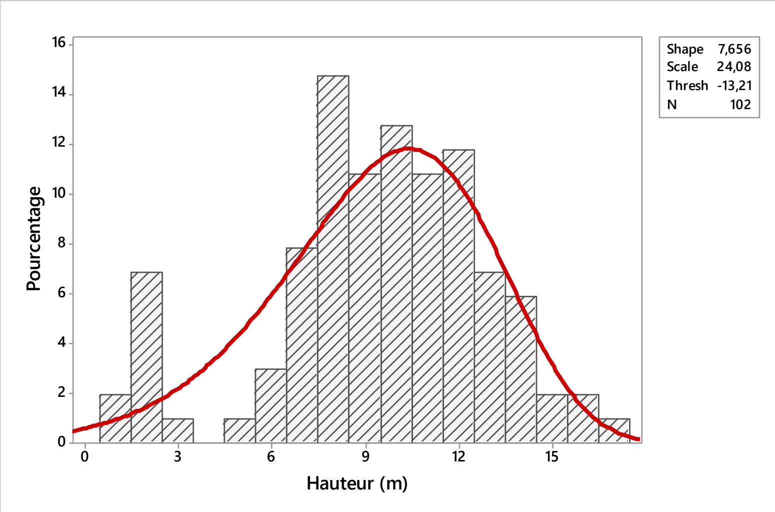
Vertical structure is assessed based on the height distribution of individuals in the overall stand and in the *S. birrea* population (Figures 8 and 9).



Thresh (a) = position parameter; Scale (b) = scale parameter; Shape (c) = shape parameter of the Weibull distribution

Figure 8. Vertical structure of woody vegetation in the stand

Analysis of the height distribution of the stand reveals a left-sided asymmetry, with a shape parameter (c) equal to 1.132. The stand is mainly composed of individuals between 0.1 m and 5 m tall.



(Thresh (a) = position parameter; Scale (b) = scale parameter; Shape (c) = shape parameter of the Weibull distribution).

Figure 9. Vertical structure of the *S. birrea* population

The histogram of the distribution of individuals according to height (Fig. 9) shows a bell shape, with a marked absence of individuals of low height (less than 6 m) and a predominance of individuals reaching around 10 m in height. The shape parameter (c) has a high value of 7.656. Individuals with heights between 8 m and 12 m are the most represented, with a modal class observed between 7 m and 8 m.

Diversity underpins all terrestrial ecosystems and provides the life support systems on which all existence depends [45]. This study was conducted using a sampling design that characterized 31 woody species, involving a total of 1634 individuals for measurements of dendrometric parameters. The number of species inventoried in this study is higher than those reported by [16] and [30], who found 11 species in 9 genera and 8 families, respectively. Compared with the work of [33] on the "Flora and structure of woody vegetation along the Great Green Wall in the Ferlo, northern Senegal", the results are almost similar, with 20 species belonging to 18 genera and 12 families listed.

The flora of the study area is dominated by two families: *Fabaceae* (25.81%) and *Combretaceae* (19.35%). Two other families are relatively well represented: *Apocynaceae* (12.90%) and *Malvaceae* (6.45%). These results are like those of [33] and [34], who also showed that *Fabaceae, Combretaceae* and *Apocynaceae* are the most represented families in the northern Ferlo. The strong presence of Fabaceae could be explained by their ability to fix atmospheric nitrogen and their abundant production of viable seeds over a long period [15].

The high numbers of *Fabaceae* and *Malvaceae* could be explained by taxonomic considerations, in particular the use of the APG III classification, which groups the *Caesalpinaceae*, *Fabaceae* and *Mimosaceae* into a single family (*Fabaceae*), and the *Bombacaceae, Tiliaceae* and *Sterculiaceae* into the *Malvaceae* family.

The stand structure established according to biological type shows that almost all the species encountered are phanerophytes, except for a single geophyte (*Tinospora bakis*). The high presence of phanerophytes suggests that this area has the appearance of a forest, in line with the observations of [48] and [19]. On the other hand, the low presence of therophytes could be explained by the density of the phanerophyte populations, which only favors the presence of undergrowth herbaceous plants. This result does not corroborate those of [18], who observed mainly phanerophytes in the same area in Ferlo. The presence of geophytes could be explained by their mode of vegetative reproduction in the form of tubers or bulbs, allowing them to persist even after major disturbances [6, 14].

In terms of geographical distribution, the flora of our zone is dominated by African (Af) (48.39%) and Afro-Asian (As) (38.71%) species. This dominance could be explained by the country's continental position and the adaptation of these species to the bioclimatic conditions of the area [36]; [6]; [14]. Regarding phytogeographical affinities, this study showed that the environment is dominated by Sahelo-Sudanian (sa-so) species with 58.06%, followed by Sahelian (sa) species with 16.13%. The remainder was occupied by Sudanian and Sudano-Sahelian species (12.90%). These results corroborate those of [45]. The multiple droughts in the area are thought to have led to a reduction in the density of species with Guinean and Sudano-Sahelian affinities, but it is mainly human activities that have contributed to their disappearance [46]. According to [41] and [33], woody species (*S. birrea*, *B. aegyptiaca*, *B. senegalensis*, etc.) are highly prized by indigenous populations. All their parts are used, and with the increase in the pastoral population (human and bovine) and their sedentarisation, these woody species have ended up disappearing or surviving only as old, isolated individuals. This disappearance of woody species has led to the migration or death of fauna, disrupting the life cycle of these formations and occupation by sclerophyllous species that provide fewer ecosystem services and prevent the establishment of other types of species. This confirms the trend towards the homogenization of species and formations noted by certain authors [15]; [35]. This homogenization is thought to be the result of a deterioration in the quality of woody stands.

The results of this study show that the most abundant species is *Calotropis procera* with a relative abundance of 33.17%, followed by *Balanites aegyptiaca* (25.09%) and *Boscia senegalensis* (24.05%). These results are confirmed by those of [29] and [42], who worked in part of our study area. The adaptation of these three species can be explained by their ability to withstand climatic constraints and anthropogenic pressures. *Balanites aegyptiaca*, with its reduced leaves, spines and photosynthetic branches that are active all year round, and *B. senegalensis*, with its leathery, evergreen leaves, show great resilience. Studies have shown that the colonisation of the environment by these species is due to the impoverishment of the soil following numerous droughts [5]. This result confirms those of [46] and [4], who state that the presence of species such as *Calotropis procera* is an indicator of environmental degradation. Other species such as *Sclerocarya birrea*, *Adansonia digitata*, *Pterocarpus lucens*, and *Combretum glutinosum* are less abundant, their individuals being found in isolation.

The dominance index shows that species such as *Adansonia digitata*, *Sclerocarya birrea* and *Boscia senegalensis* dominate this environment with proportions of 22.79%, 21.40% and 18.15% respectively. Species such as *Balanites aegyptiaca*, *Acacia ehrenbergiana*, *Terminalia avicennoides, Guiera senegalensis* and *Acacia raddiana* have a dominance index of 12.38%, 6.03%, 3.47% and 2.35% respectively. This dominance could be linked to the multi-celled characteristics of the trunks of *Boscia* and *Calotropis*, as well as to the old age of the *Sclerocarya birrea* and *Combretum glutinosum* trees. Similarly, according to [16], the presence of scattered individuals such as those of the *Combretaceae* and other families in our study indicates that the vegetation is evolving under difficult climatic and/or anthropogenic conditions.

In terms of the importance value index (IVI), the dominant species are *Boscia senegalensis* (62.75%), *Balanites aegyptiaca* (53.03%), *Calotropis procera* (48.19%), *Sclerocarya birrea* (34.87%) and *Leptadenia lanceolata* (13.83%). The same trend has been highlighted by several authors [38, 49, 44] cited by [2] and by [31]. The work of these authors revealed a clear regression of *Sclerocarya birrea*, *Combretum glutinosum*, *Acacia senegal*, and an expansion of *Boscia senegalensis*, *Balanites aegyptiaca*, *Calotropis procera*, etc. Poupon has shown that rainfall is a determining factor for vegetation in the Sahelian zone. Similarly, a study of the characteristics of the woody stand in the Ferlo showed that several species with Guinean phytogeographical affinities have become very rare or even disappeared due to repeated droughts [28]. These results corroborate those of [5], who showed that the Ferlo is now colonized by sclerophyllous species because of soil impoverishment.

The Shannon index expresses diversity by considering the number of species and the abundance of individuals within each of these species. A community dominated by a single species will have a lower coefficient than a community in which all the species are co-dominant. The value of the Shannon-Weaver index varies from 0 (a single species, or one species largely dominating all the others) to log S (when all the species have the same abundance) [21]. The species that make up the steppes are sclerophyllous species par excellence. The biological diversity of the environment was assessed using the Shannon and Pielou equitability indices. The values of the Shannon index (2.54 bits) and equitability (0.51 bits) of the population show that the environment is not very diverse, but that a few species dominate in terms of representativeness (*Balanites aegyptiaca*, *Boscia senegalensis*, etc.). Our results are confirmed by authors such as [29], [5]and [41].

Of all the surveys carried out, 1634 individuals were listed, i.e. a density. Basal area is a criterion used to assess the dynamics of a population based on its DBH (diameter at breast height) and the condition of a species in a stand. Basal area is small and varies from species to species. The basal area is equal to 8.83 m²/ha in the overall stand, which can be explained by the presence of a large community of small-diameter trees, reflecting a predominantly shrubby stand.

Aerial cover is 1550.01 m²/ha. *Balanites aegyptiaca*, *Sclerocarya birrea*, *Boscia senegalensis* and *Calotropis procera* alone cover more than half of the surface area, with 37.87%, 10.16%, 7.73% and 22.39% respectively. The high aerial cover in this environment is explained by the presence of large trees with contiguous crowns, such as *Adansonia digitata*.

The structure of the stand according to circumference shows that around 35% of the trees have a circumference of less than 50 cm, with a clear dominance of the class between 10 and 20 cm. The curve shows a positive asymmetric distribution (straight asymmetry) with a shape parameter c equal to 1.132. This may indicate a low regeneration potential due to exogenous actions, especially in the smaller diameter classes. The low representativeness of individuals with a circumference greater than 100 cm could be explained by their exploitation for charcoal and firewood, as well as the use of their aerial part (foliage) as fodder for livestock in the dry season [33].

The demographic structure of the *S. birrea* population shows a bell-shaped structure with straight asymmetry. The shape parameter c is equal to 2.437, indicating that young trees are virtually absent or very poorly represented. Trees with a circumference of between 50 cm and 150 cm are the most numerous. This structure is characteristic of degraded populations with very low regeneration potential due to human pressures and may also indicate populations in extinction. In the Sahelo-Sudanian zone of Niger, the same observation was made by [17] on four woody fruit species (*Adansonia digitata*, *Vitellaria paradoxa*, *Tamarindus indica* and *Parkia biglobosa*), and in Benin by [24] on *S. birrea*. Our results show that the *S. birrea* population is therefore unstable and ageing. These results are corroborated by those of [47] working in the Ferlo and those of [1] in the Sahelian zone of Niger.

The height distribution of the stand shows a straight asymmetry with the shape parameter c equal to 1.132. The stand is dominated by many young individuals and a small number of adult individuals, posing a problem of recruitment of young individuals into the older classes. This constitutes a decision-making tool for the forester in managing the stand. Individuals in the stand with a dbh of between 0 and 6 cm dominate the environment. Individuals with a dbh greater than 18 cm are poorly represented, but their presence is essential for the balance of this type of stand.

These results agree with those of [33] working on the characterization of Sahelian woody vegetation in Senegal. These authors showed a predominance of the shrub stratum in the vertical structure, like the results of [15] who confirmed good regeneration of resistant woody species. They also showed that most woody species are found in the lower stratum (less than 5 m high), where human pressure and climatic hazards prevent regenerated individuals from developing and freeing themselves from the shrub layer.

Analysis of the histogram of the distribution of individuals in height in the population shows a negative asymmetric distribution (left asymmetry), characteristic of stands with a predominance of large-diameter (old) individuals. The shape parameter of the Weibull distribution is 7.456, greater than 3.6. The results show that most of the trees are between 7 m and 16 m tall. According to [37], this distribution reflects declining, disturbed or ageing populations. Other studies have also revealed regressive trends in ageing populations of *S. birrea* in Benin [24]. It may also be characteristic of degraded populations with very low regeneration potential due to anthropogenic pressures, potentially indicating populations in extinction.

Information on the plant structure showed that the stand regenerates well, with a strong presence of species from lower dbh classes, hence the high proportions of regeneration (over 50%). Specifically, *Calotropis procera* (35.31%), *Boscia senegalensis* (20.31%), *Balanites aegyptiaca* (18.05%) and *Leptadenia lanceolata* (15.52%) appear to be the species with the highest regeneration rates in the stand. The strong presence of these species could be explained by their competitiveness, as according to [12], competition is one of the major mechanisms explaining the absence of certain species in a plant community. According to [11], individuals derived from stump sprouts probably have a better chance of survival than woody plants derived from germination. The species *Calotropis procera* and *Boscia senegalensis* are said to be less palatable to livestock and less used for ethnobotanical purposes than other species [32].

The regeneration of most of the species recorded in Ferlo bears witness to the gradual evolution of the rangeland populations. The rate of exploitation of these stands is relatively low in Ferlo. In this area, human activity is mainly reflected in the selective pruning and cutting of *Balanites aegyptiaca*, *Acacia tortilis* var. *raddiana* and *Dalbergia melanoxylon*, but also in the significant mortality of individuals of *Boscia senegalensis, Calotropis procera* and sometimes even *Balanites aegyptiaca*. Most of these species have multiple ethnobotanical uses, as shown by the work of [30]. Species such as *Leptadenia pyrotechnica*, *Acacia raddiana*, *Acacia senegal* and *Sclerocarya birrea* have a regeneration rate of between 0.5% and 3%, while the remaining species do not regenerate. The species *Acacia ehrenbergiana, Acacia pennata, Adansonia digitata, Adenium obesum, Anogeissus leiocarpus, Combretum aculeatum, Combretum glutinosum, Combretum micrantum, Commiphora africana, Feretia apodanthera, Maytenus senegalensis, Piliostigma reticulatum, Sterculia setigera, Stereospermum kunthianum, Terminalia avicennioides, Tinospora bakis* and *Ziziphus mauritiana*do not regenerate.

Conclusion

The aim of this study, carried out in the sandy Ferlo in northern Senegal, was to provide information on the dendrometric characteristics of a *Sclerocarya birrea* woody stand to promote better conservation of biodiversity and ecosystem services. The results reveal a diverse flora made up of 31 species divided into 24 genera and 15 families, with a predominance of *Fabaceae*, *Combretaceae*, *Apocynaceae* and *Malvaceae*, accounting for 65.38% of the species recorded. The biogeographical distribution shows a predominance of Sahelo-Sudanian species (58.06%), followed by Sahelian species (16.13%). Despite the dominance of Sahelian species, species with Sudanese and Guinean affinities, such as *Calotropis procera*, *Balanites aegyptiaca* and *Boscia senegalensis*, persist in the region.

The study highlights the dominance of the shrub layer in the environment. The woody stratum shows positive development thanks to a strong representation of young individuals and good regeneration. On the other hand, the *S. birrea* population shows an opposite dynamic. Large girth individuals dominate, characterizing an aging and unstable population with almost non-existent regeneration. To restore the *S. birrea* population to its normal structure, extensive management and a program of assisted regeneration (RNA) are required. Such intervention is crucial to avoid the decline of this species due to regeneration problems.

This ecological study of *S. birrea* offers valuable insights into the silviculture of this plant, complemented by an analysis that makes it possible to predict periods of resource availability in the region. Regeneration, reforestation and monitoring strategies are essential to improve the conservation of biodiversity and ecosystem services in the Ferlo. These measures will help to maintain biodiversity and strengthen the resilience of ecosystems in the face of climate change and human pressures.

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