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Influence of Topography on the Distribution and Structure of Woody Plants in the Senegalese Sahel (Sandy Ferlo)

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Abstract

This study describes the floristic composition and structure of a woody stand in the Senegalese Sahel, paying particular attention to the edaphic factors of its floristic composition. A stratified inventory considering the different relief units was adopted. Woody vegetation was surveyed using a dendrometric approach. The results obtained show that the flora is dominated by a few species adapted to drought, such as *Balanites aegyptiaca* (L.) Del., *Calotropis procera* Ait. and *Boscia senegalensis* (Pers.). The distribution of this flora and the structure of the ligneous plants are linked to the topography. In the lowlands, the flora is more diversified and the ligneous plants reach their optimum level of development compared with the higher relief areas. In the lowlands, there are a few woody species which, in the past, were indicative of better climatic conditions. These are *Anogeissus leiocarpus* (DC.), *Commiphora africana* (A. Rich.), *Feretia apodanthera* Del., *Loeseneriella africana* (A. Smith), *Mitragyna inermis* (Willd.) and *Sclerocarya birrea* (A. Rich). It is important that their reintroduction into reforestation projects takes account of their edaphic preference.

Keywords

Woody Plants, Distribution, Topography, Ferlo, Senegal

1. Introduction

In semi-arid regions, the distribution of vegetation reflects natural variations in the physical environment, in particular soil type and rainfall [1]. The nuances of the water regime are at the root of a strong differentiation of plant formations [2] [3] accentuated by the topography [4]. Under conditions of ecological constraint, niche differentiation remains essential for the survival of woody plants, particularly those that are most demanding in terms of certain mineral constituents in the soil [5]. Following the repeated failures recorded during silvicultural reforestation and revegetation operations in the Sahelian zone [6], the edaphic ranges of species distribution in the bio-pedoclimatic subdivisions of the Sahel need to be better known. In the Sahel region of Senegal, specifically in the sandy part, the variability of environmental characteristics in relation to the distribution of woody species has not been sufficiently studied; the existing data are very old [7] [8] [9]. The most recent data are based on exhaustive descriptions of the geographical distribution of woody species without taking into account the variability linked to topography [10] [11] [12] [13]. On the other hand, the influence of geomorphology on the distribution of vegetation has been highlighted in the south, in the Sudano-Sahelian and Sudanian zones of Senegal by Andrieu [14]. This study was carried out in northern Senegal, in the context of the Great Green Wall (GGW). The GGW is a transcontinental project that aims to reforest 15 million hectares in a strip 7700 km long and 15 km wide between Dakar and Djibouti [6].

To optimise the success of phyto-restoration operations, the experts were asked to refine their research into the ecology of existing species [6]. The present study is therefore justified by the need to update existing data and to clearly identify the edaphic preferences of woody species in order to contribute to the development of management tools in the Great Green Wall zone. Specifically, the study will describe the floristic composition, distribution and structure of the woody stands, paying particular attention to the topographical determinants of this distribution.

2. Material and Method

2.1. The Study Area

The Ferlo is one of Senegal's largest climatic zones, located in the Senegalese Sahel and covering an area of around 70,000 km^2, or 28% of the national territory (**Figure 1**).

The climate of the Ferlo is typically Sahelian, with two alternating seasons, a rainy season and a dry season [10]; the rainy season lasts between two and three months (between July and September) and is characterized by annual rainfall of between 200 and 400 mm/year, accompanied by a high degree of instability in time, estimated at between 30% and 40% [10]. Rainfall is one of the factors that determine the dynamics of ecosystems in this zone; the normal rainfall, which was 500 mm between 1931 and 1960 in the Senegalese sahel, has migrated more than 200 km southwards [15]. Temperatures average between 35˚C and 43˚C, reaching 45˚C in some places [16].

The relief of the sandy Ferlo combines low, monotonous plateaus with sandy

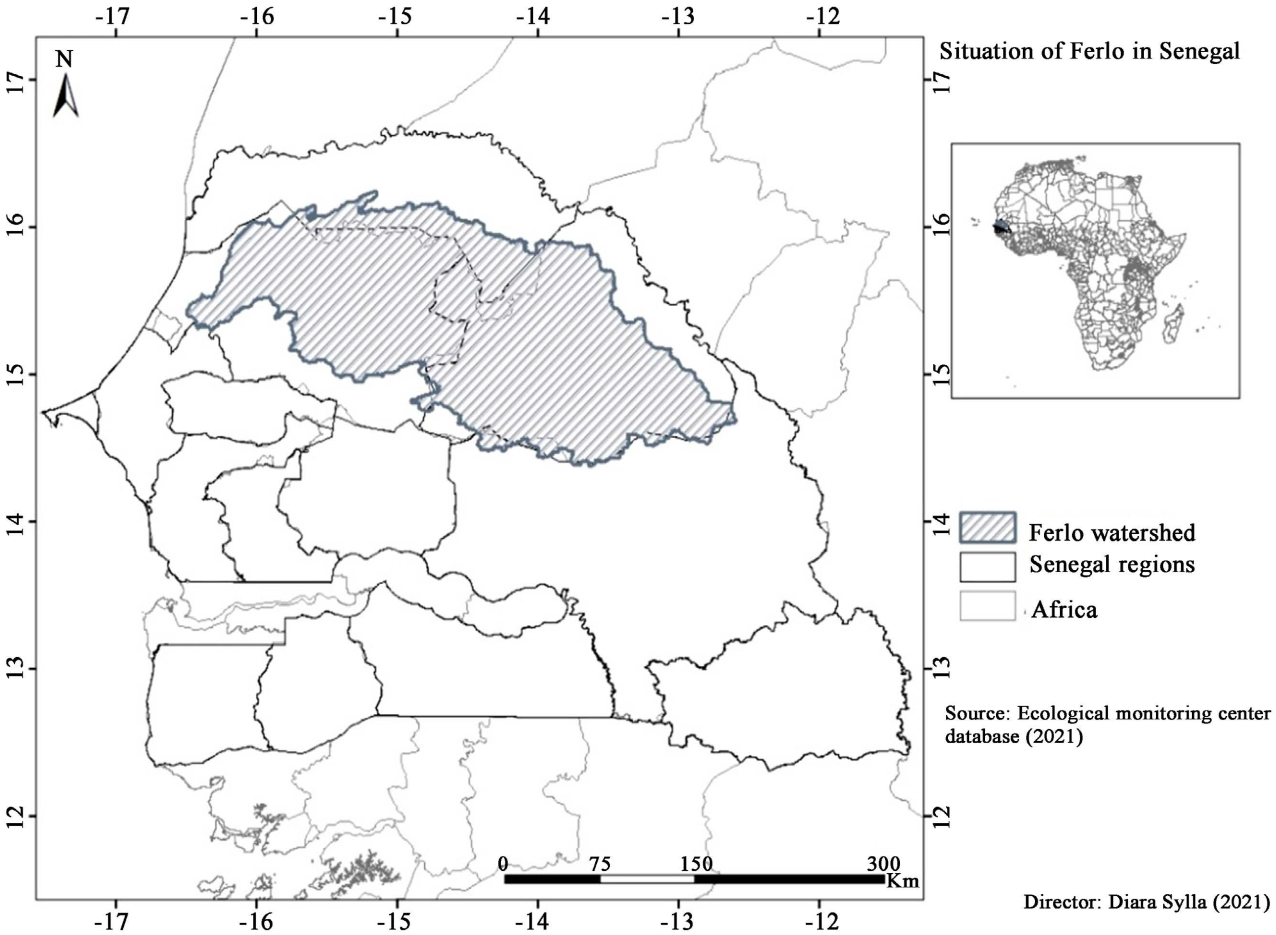

Figure 1. Location of the study area in Senegal.

accumulations forming dunes separated by shallows occupied by temporary pools during the rainy season [17]. This part of the Sahel is occupied by tropical ferruginous soils with a sandy to sandy-clay texture. These soils are poorly leached, red or ochre in colour and poor in organic matter.

At the end of the rainy season, the vegetation takes the form of a continuous herbaceous carpet dotted with frequently thorny trees and shrubs that never form a continuous stratum [18], dominated by *Balanites aegyptiaca* (L.) Del, *Boscia senegalensis* (Pers.) Lam. Ex Poir, *Acacia senegal* (L.), *Acacia tortilis* (Forsk.) Hayne ssp. *raddiana* (Savi) Brenan, and *Calotropis procera* (Aiton) [8] [10] [12] [19].

The study was carried out in the sandy Ferlo on a section located between 15˚04' and 15˚59' North latitude and between 15˚42' and 15˚20' West longitude. Five sites arranged along two transects were defined between isohyets 300 and 400 mm: a N.NE-S.SW transect, Widou Thiengoly - Tessékéré - Labgar, and a W.N-E.SE transect, Widou Thiengoly - Kamb - Déali (**Figure 2**).

2.2. Wood Inventory

The dendrometric vegetation survey method was applied to woody stands. The sampling unit was a 2500 m² plot, as recommended by Boudet [20] for Sahelian

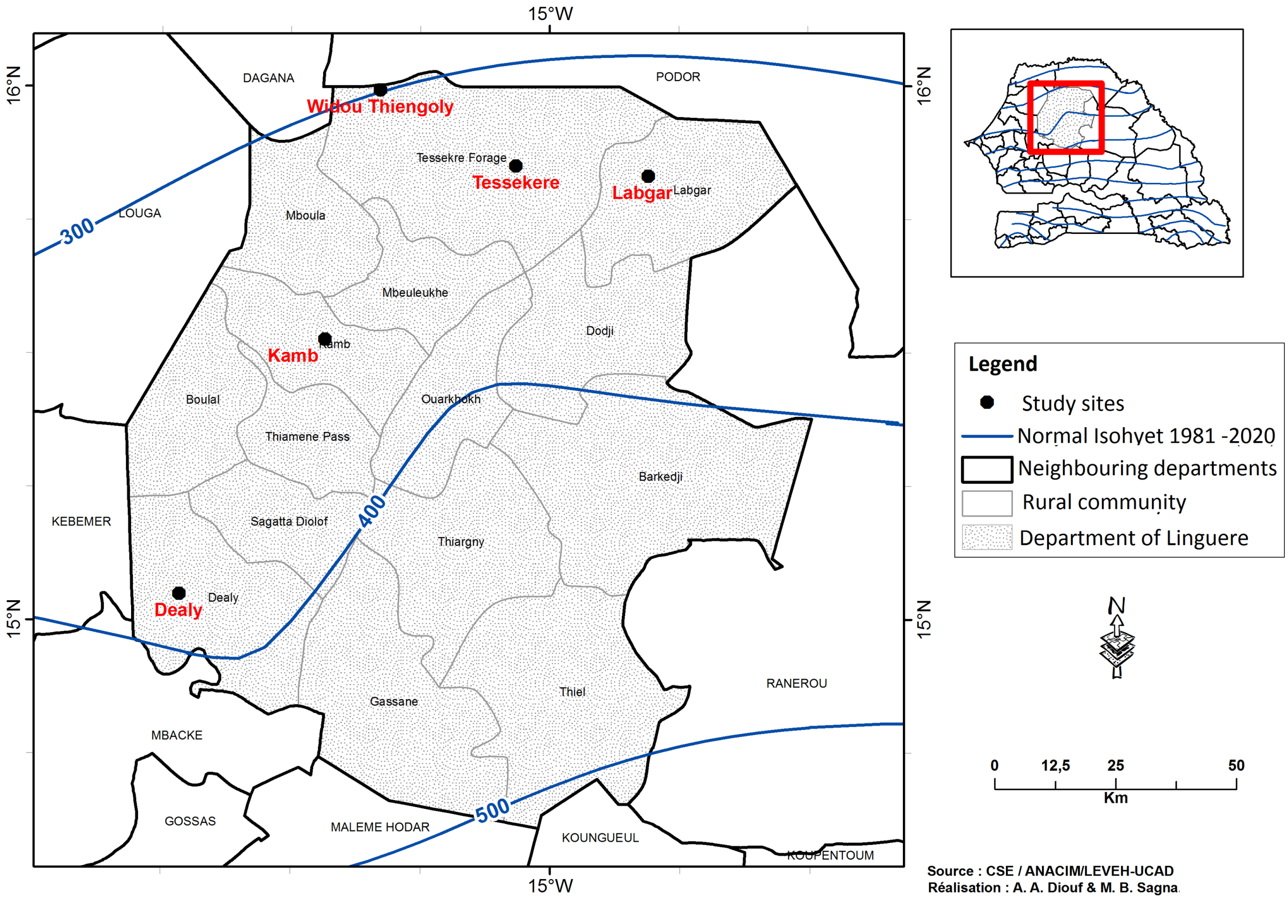

Figure 2. Study sites.

ecosystems. In each inventory plot, all woody plants with a circumference of 10 cm or more at 30 cm from the ground were identified and measured. The choice of this level of measurement was dictated by the fact that many shrubs are branched below 1.3 m [21], which is the height at which the measurement is usually taken. Individuals with a circumference of less than 10 cm are regenerated. The scientific names of the species have been transcribed using the Flore in Senegal [22], and updated according to the enumeration of the Plants with Flowers of Tropical Africa [23].

Given the variability associated with topography, stratified sampling based on geomorphological units was used, as recommended by Gounot [24]. It also takes into account the representativeness of the relief units. On each geomorphological formation, a survey was carried out at random and successively on each topographical unit (flats, slopes, shallows and hillocks). The sample consisted of 144 plots, including 50 on the flats and 28 on each of the other units (slopes, shallows and knolls). The imbalance observed in this sample can be explained by the greater frequency of the flats compared with the other topographical units.

2.3. Data Processing

The floristic list was drawn up according to the different taxonomic groups (families, genera and species). Real (D) and relative (Dr) densities were calculated using the following formulae [25]:

$$D = Ni/S$$

where Ni is the total number of animals in sample i and S is the area of the sample in ha.

$$\mathrm{Dr}(\%) = (n/N)/100$$

where n is the number of individuals of one species and N is the number of individuals of all species in the stand.

Cover (R) is estimated by the circular model of average tree crown diameter. It is calculated from the following formula [25]:

$$R(\%) = \left(\sum Rh/S\right) \times 100 : Rh = \pi \times \left(Dm^2/4\right)$$

where Rh is the surface area of the aerial canopy (in m^2), Dm the average crown diameter (in m) and S the surface area of the sample considered in ha.

The basal area (St), which corresponds to the sum of the cross-sections of the trees at 0.30 m from the ground, is calculated using the following formula:

$$\sum_{a=1}^{n} \left(\mathrm{Ca}^2/4\pi\right)$$

where Ca is the circumference of the tree at 0.30 m above the ground

The structure of the woody stand was assessed through the distribution of individuals in height classes and circumference classes.

To highlight the topographical determinants of the distribution of woody plants, data from soil analysis and vegetation surveys were subjected to Correspondence Factor Analysis (CFA) using R software.

3. Results

3.1. Floristic Composition and Importance

The surveys revealed 35 species, unevenly distributed between the different topographical units. In the shallows and flats, the species richness is higher (27 and 24 species respectively) than on the slopes and hillsides, which contain 13 and 11 species respectively (**Table 1**). A few species of this woody flora make up most of the individuals in the stand studied (column P in the table). These are *Balanites aegyptiaca* (57.5%), *Calotropis procera* (14.1%), *Acacia tortilis raddiana* (6.6%), *Leptadenia hastata* (5.2%) and *Boscia senegalensis* (4.6%). Out of a total of 2013 individuals inventoried in the stand, half are found in the lowlands (50.6%), followed by the flats (30.5%). Slopes and knolls are less populated (8.6% and 10.2% respectively).

3.2. Spatial Distribution of Woody Flora

The relationships between topographical units and floristic composition were studied using Correspondence Factorial Analysis (CFA). It is important to note, however, that species represented by 1 to 3 individuals were not taken into

Table 1. List of woody species surveyed and frequency (in %) in relation to the stand as a whole.

Famille	Genre Espèce	Code	L	F	S	M	P
ANACARDIACEAE	*Sclerocarya birrea* (A. Rich)	*Sbir*	0.30	0.50	0.20	0.10	1.09
APOCYNACEAE	*Adenium obesum* (Forsk.)	*Aob*	0.00	0.05	0.10	0.10	0.25
ASCLEPIADACEAE	*Calotropis procera* Ait.	*Cpro*	9.04	1.99	1.49	1.59	14.11
	Leptadenia hastata (Pers.)	*Lhas*	3.03	0.45	0.89	0.84	5.22
	Leptadenia pyrotechnica (Forsk.)	*Lpyr*	0.00	0.00	0.35	0.10	0.45
BALANITACEAE	*Balanites aegyptiaca* (L.) Del.	*Beag*	28.27	20.42	2.93	5.86	57.48
BIGNONIACEAE	*Stereospermu kunthianum* Cham.	*Skun*	0.05	0.00	0.00	0.00	0.05
BOMBACACEAE	*Adansonia digitata* (L.)	*Adig*	0.30	0.20	0.00	0.00	0.50
BURSERACEAE	*Commiphora africana* (A. Rich.)	*Cafr*	0.05	0.15	0.00	0.00	0.20
CAESALPINIACEAE	*Bauhinia rufescens* Lam	*Bruf*	0.00	0.05	0.00	0.00	0.05
	Pilostigma reticulatum (DC.)	*Pret*	0.00	0.05	0.00	0.00	0.05
	Tamarindus indica L.	*Tind*	0.05	0.00	0.00	0.00	0.05
CAPPARIDACEAE	*Boscia senegalensis* (Pers.)	*Bsen*	0.79	1.59	1.49	0.75	4.62
COMBRETACEAE	*Anogeissus leiocarpus* (DC.)	*Alei*	1.09	0.15	0.00	0.00	1.24
	Combretum glutinosum perr.ex DC	*Cglu*	0.25	1.34	0.15	0.10	1.84
	Combretum aculeatum Vent.	*Cacu*	0.05	0.00	0.00	0.00	0.05
	Combretum micranthum G. Don	*Cmic*	0.10	0.00	0.00	0.00	0.10
	Guiera senegalensis J.F.Gmel	*Gsen*	0.40	0.05	0.00	0.00	0.45
	Terminalia avicennioides G.et Perr.	*Tavi*	0.20	0.00	0.00	0.00	0.20
EPHORBIACEAE	*Jatropha chavalieri* Beille	*Jche*	0.05	0.00	0.00	0.00	0.05
HIPPOCRATEACEAE	*Loeseneriella africana* (A. Smith)	*Lafr*	0.05	0.00	0.00	0.00	0.05
FABACEAE	*Acacia senegal* (L.)	*Asen*	0.50	0.60	0.50	0.30	1.89
	Acacia seyal Del.	*Asey*	0.15	0.15	0.05	0.05	0.40
	Acacia tortilis raddiana (Forst.)	*Arad*	3.83	2.19	0.40	0.15	6.56
	Acacia nilotica (L.)	*Anil*	0.89	0.05	0.05	0.00	0.99
	Acacia pennata (L.)	*Apen*	0.00	0.05	0.00	0.00	0.05
	Dichrostachys cinerea (L.)	*Dcin*	0.00	0.05	0.00	0.00	0.05
	Faidherbia albida (Del.)	*Falb*	0.00	0.10	0.00	0.00	0.10
	Dalbergia melanoxylon G. Perr	*Dmel*	0.05	0.30	0.00	0.00	0.35
MERISPERMACEAE	*Tinospora bakis* (A. Rich)	*Tbak*	0.00	0.05	0.00	0.00	0.05
RHAMNACEAE	*Zizyphus mauritiana* Lam.	*Zmau*	0.10	0.20	0.05	0.00	0.35
RUBIACEAE	*Feretia apodanthera* Del.	*Fapo*	0.30	0.00	0.00	0.00	0.30
	Mitragyna inermis (Willd.)	*Mine*	0.40	0.00	0.00	0.00	0.40
TILIACEAE	*Grewia bicolor* Juss.	*Gbic*	0.30	0.10	0.00	0.00	0.40
STERCULIACEAE	*Sterculia setigera* (Del.)	*Sset*	0.05	0.00	0.00	0.00	0.05
Number of species			27	24	13	11	35
Proportion of woody trees (%)			50,62	30.50	8.64	10.23	100

L= Lowlands; F = Flats; S = Slopes; M= Mounds W= Woody stand.

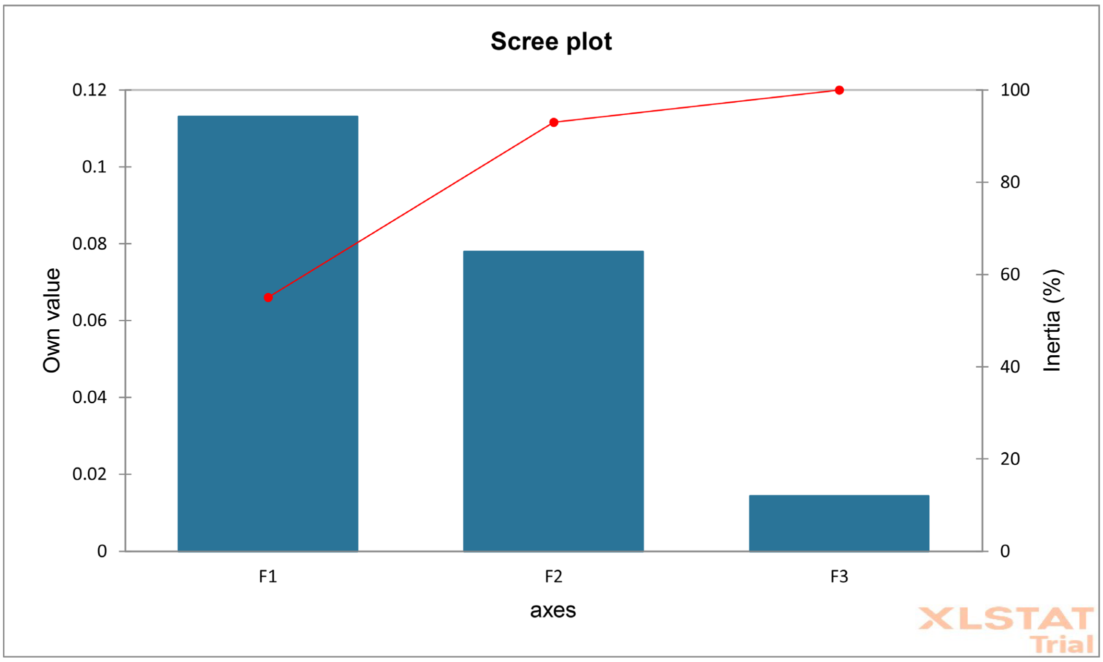

Figure 3. Eigenvalue and percentage variance of the CFA axes.

account, since this method does not provide sufficient information on their ecological preference. The rarest of these ligneous species are represented by one individual in our sample. This stand is made up of trees (*Stereospermu kunthianum*, *Tamarindus indica*, *Loeseneriella africana and Sterculia setigera*) and shrubs (*Combretum aculeatum*, *Combretum micranthum*, *Jatropha chavalieri*, *Acacia pennata*, *Tinospora bakis*). **Figure 3** shows the proportion of information contained in the CFA axes. The first two axes, which account for 95.3% of the total variability, were selected. They contributed 56.4% and 38.4% respectively.

The distribution of species in the stand in this plane shows fairly clear discrimination between three groups of species (**Figure 4**).

The plane formed by the first two axes of the CFA clearly distinguishes three groups: group 1 (Gr1), which can be identified at the negative abscissas of F1 and the positive abscissas of axis 2, group 2 (Gr2), which can be identified at the positive abscissas of F1 and F2, and group 3 (Gr3), located at the negative abscissas of F2.

Group 1 (Gr1) includes species with a clear preference for lowlands*: Acacia nilotica* [Ani], *Anogeissus leiocarpus* [Alei], *Feretia apodanthera* [Fapo], *Grewia bicolor* [Gbic], *Guiera senegalensis* [Gsen], *Mitragyna inermis* [Mine], and *Terminalia avicennioides* [Tavi].

Group 2 (Gr2) features two species found mainly on hillocks and slopes: *Adenium obesum* [Aob], *Acacia senegal* [Asen], *Boscia senegalensis* [Bsen], *Leptadenia pyrotechnica* [Lpyr], *Leptadenia hastata* [Lhas] and *Sclerocarya birrea* [Sbir].

Group 3 (Gr3) is made up of flat areas, which are the preferred habitats of *Combretum glutinosum* [Cglu], *Commiphora africana* [Cafr], *Dalbergia melanoxylon* [Dmel], *Faidherbia albida* [Falb] and *Zizyphus mauritiana* [Zmau].

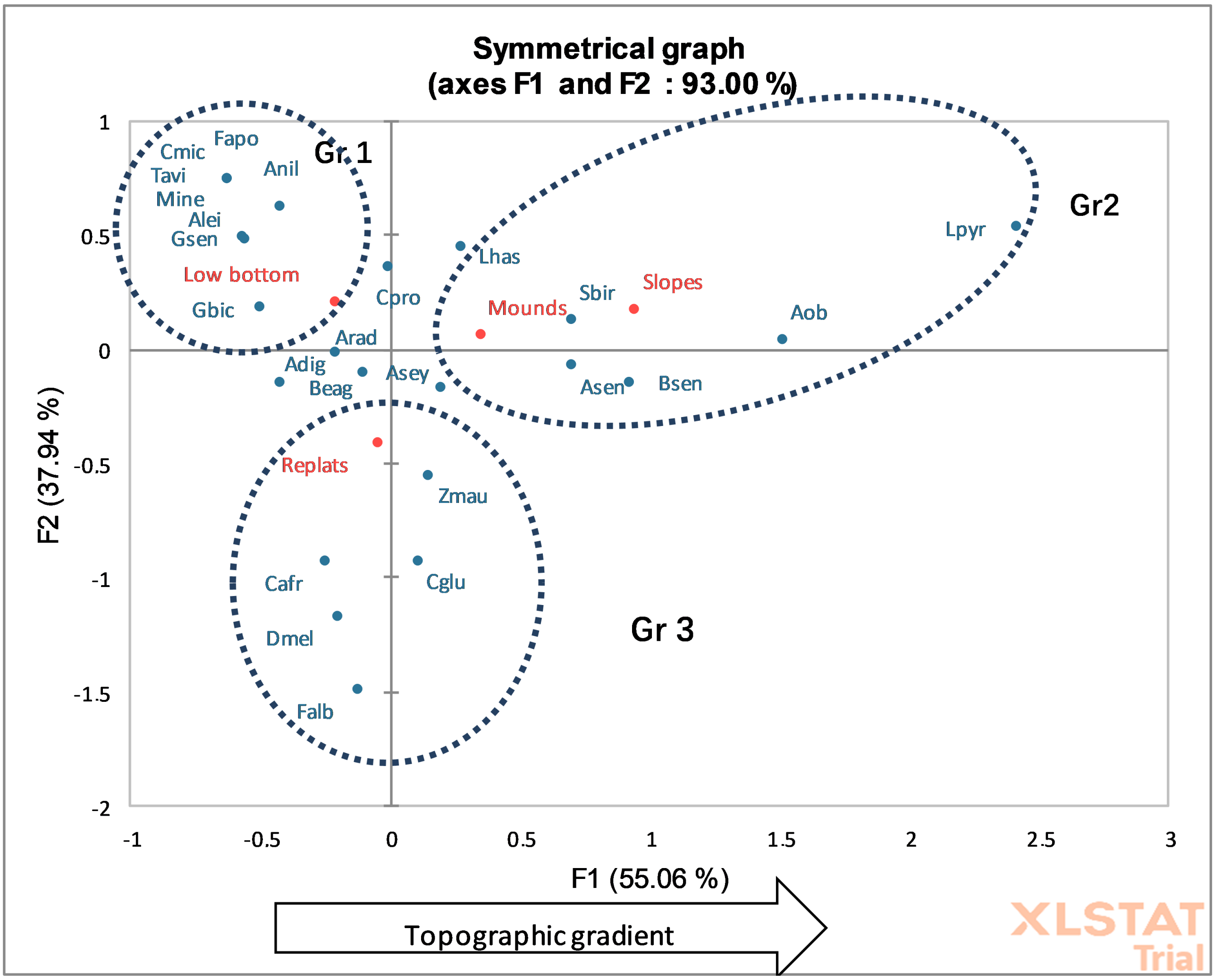

Figure 4. Distribution of some stand species on the F1 × F2 plane.

The CFA brings together a large number of stand species at the center of the factorial plane. These are species that colonize several of the topographical units at least to some extent. These are *Adansonia digitata* [Adig], *Acacia seyal* [Asey], *Acacia tortilis raddiana* [Arad], *Balanites aegyptiaca* [Beag], and *Calotropis procera* [Cpro].

3.3. Densities, Basal Areas and Cover

Some information on stand density, basal area and cover is given in Table 2.

Values with different letters are statistically different according to the KRUSKAL-WALLIS test (significant differences for p-value < 0.05). Only trees with a trunk circumference greater than 10 cm at 30 cm above ground are considered.

The mean values for density, basal area and woody cover are higher in the shallows and on the flats than on the slopes and knolls. They are also higher than the averages obtained for the entire stand in the study area, indicating the relatively high maturity of the woody species in these two topographical units.

3.4. Horizontal and Vertical Stratification of Woody Plants

Figure 5 and Figure 6 show, for each topographical unit respectively, the distribution of ligneous plants according to their circumference and height.

The histograms obtained indicate that the distribution of woody plants according to their structure is dependent on topography. These distributions are of three types:

- Bell-shaped in the shallows and on the slopes. The middle height and trunk diameter classes are the most abundant, indicating a lack of stand renewal.

Table 2. Average values for density, basal area and cover as a function of the topographical unit considered.

		Density (individuals/ha)	Basal area (m^2/ha)	Cover (%)
Total stand		108 ± 87	4.20 ± 2.31	14.6 ± 9.6
Topographic unit	Lowlands	262 ± 84[a]	12.1 ± 5.25[a]	40.7 ± 15[a]
	Flats	155 ± 44[b]	7.74 ± 3.10[a]	18.2 ± 7.8[b]
	Slopes	62 ± 31[c]	1.64 ± 0.54[b]	7.6 ± 3.6[c]
	Mounds	54 ± 42[c]	0.72 ± 0.33[b]	3.6 ± 1.4[d]

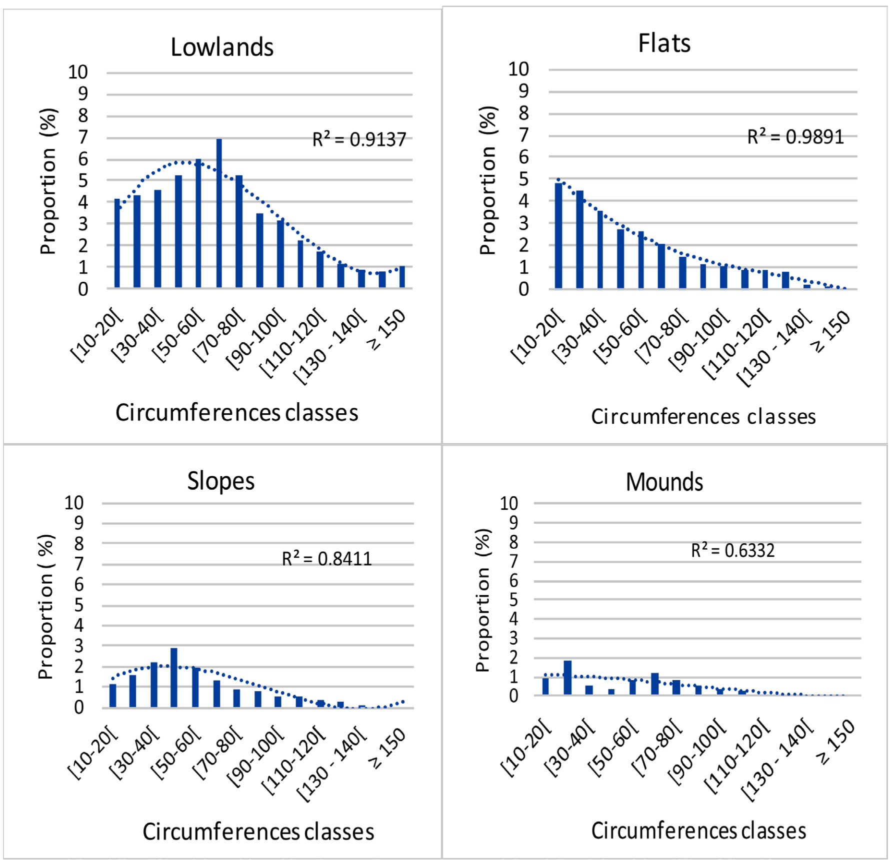

Figure 5. Distribution of the woody stand by circumference classes (in cm) in the different topographical units.

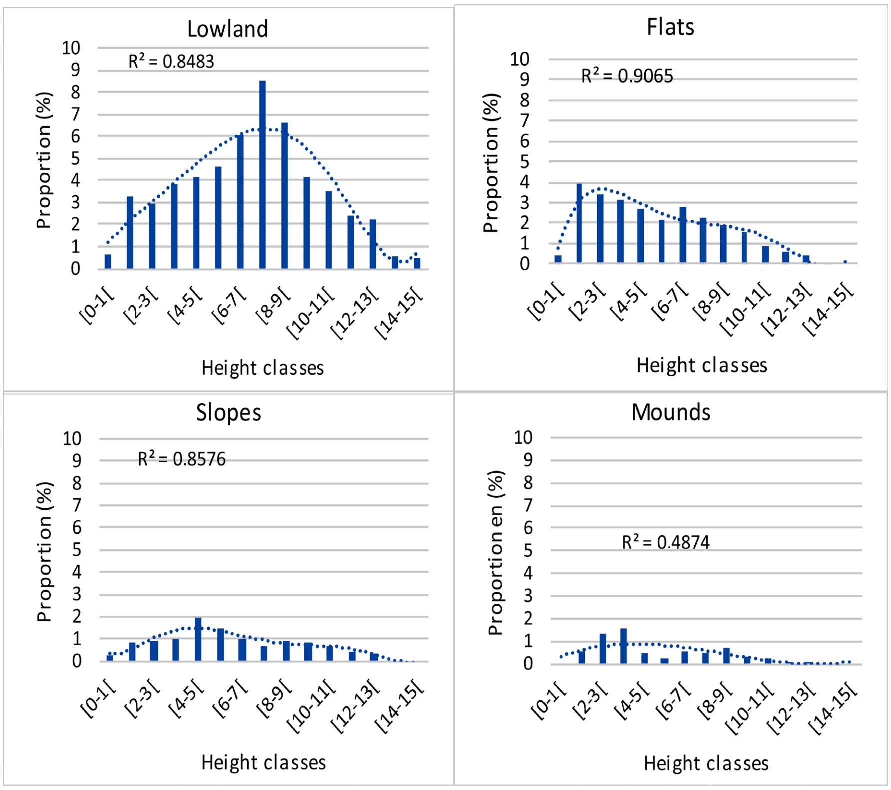

Figure 6. Distribution of woody vegetation by height classes (in m) in the different topographical units.

- Asymmetrical, with low-value classes over-represented on the flats. The shrub layer is predominant here. This type of distribution indicates active stand renewal.

- Erratic, "jagged", on the knolls, indicating a lack of individuals in several circumference and height classes.

4. Discussion

According to our counts, the flora of the Ferlo zone studied contains 35 woody species. This flora is dominated by *Acacia tortilis raddiana, Balanites aegyptiaca, Calotropis procera* and *Boscia senegalensis*, which account for more than 60% of the individuals in the stand. According to Jauffret [26], this imbalance in species structure is an indicator of the fragility of an ecosystem. In the Ferlo, the abundance of these species can be explained by their ability to adapt to climatic constraints and human pressures. *Balanites aegyptiaca* has small, deciduous, leathery, pubescent leaves and thorny branches that actively photosynthesise throughout the year, while *Boscia senegalensis* has leathery, evergreen leaves [27] [7] to effectively combat excessive transpiration [28]. Poupon [7] gave these two species a high degree of sclerophyllousness (0.84 for *Balanites aegyptiaca* and 1.24 for *Boscia senegalensis*).

Their great ecological plasticity also explains their ability to occupy different micro-habitats in which conditions are not always optimal for other woody plants. As for *Calotropis procera*, Hiernaux and Le Houerou [29] emphasize that its presence is a sign of both intense and continuous grazing; White [30], for his part, considers it to be an indicator of advanced soil degradation.

Heterogeneity linked to topography has a remarkable influence on the distribution of the flora of the Ferlo. It is thought to be one of the main causes of the differentiation of plant formations in the Sahelian zone. Woody plants thrive in low-lying areas that accumulate more water and organic and mineral matter [19].

The woody species that have a preference for these Ferlo microhabitats are: *Mitragyna inermis, Feretia apodanthera, Anogeissus leiocarpus, Guiera senegalensis, Grewia bicolor* and *Acacia seyal*. These species are considered by Bille [31] as footprints of the Ferlo fertile. Hiernaux and Le Houérou [29] report that they constitute the Sahelian forest formations of clay depressions flooded during the rainy season. During the droughts of the 1970s, 85% of *Combretum glutinosum*, 62% of *Combretum nigricans*, 54% of *Guiera senegalensis* and 96% of *Terminalia avicennioides* were decimated [1]. This is why Fall [13] says that the Combretaceae family is indicative of the bioclimatic transition in the Ferlo. These species declines are compounded by the relatively high mortality of populations of *Loeseneriella africana, Stereospermu kunthianum*, and *Sterculia setigera, Anogeissus leiocarpus, Commiphora africana, Feretia apodanthera, Mitragyna inermis*, and *Sclerocarya birrea* [1] [8] [32].

Most of these species now find their niche in the lowlands, where they are often represented by a few individuals, while some are extremely rare. According to Barry *et al*. [33], lowlands and valleys can serve as refuge areas for drought-sensitive species. During periods of drought, the distribution of these species may be limited to the valleys; this could encourage recolonization of the other relief units when rainfall becomes sufficient again. In the study area, the maintenance of mesophilous species in the lower relief units could be encouraged by the gradual increase in rainfall observed in the Sahel towards the end of the 1980s, associated with the close alternation of dry and wet years observed in recent years [34] [35] [36].

However, it is important to point out that the return of rainfall could also be fatal to certain species. Studies have shown that in the Sahelian zone, many woody plants not adapted to increasing flooding die of asphyxiation in low-lying areas and flood valleys [37].

On the highest topographical units, on the other hand, the soils are very poor, and their structure and texture favour rapid infiltration of water [18]. Rainfall is generally insufficient to replenish the underground water reserves essential for the survival of most ligneous plants [32] [33]. These topographic levels are colonised by *Balanites aegyptiaca, Boscia senegalensis* and specifically by species that are highly emblematic of aridity, namely *Adenium obesum* and *Leptadenia pyrotechnica*, which have a wider distribution range in the Sahelian zone [29].

From a structural point of view, the variations observed in the horizontal and vertical structure according to the relief units show that ligneous plants require certain conditions to develop. Low-lying areas offer the best conditions for survival, followed by flats and slopes. The erratic type of distribution, which corresponds to the stands on hillocks, could indicate a degradation of the ligneous species [38] or a disturbance of the ecological niche [39].

Most of the woody plants have not regenerated. This phenomenon could be explained by the disruption of their ecological niche. In this respect, Aronson *et al.* [40] stress the importance of low soil organic matter content in arid and semi-arid zones, as it limits both water infiltration and root penetration of young seedlings. The absence or poor regeneration of certain woody species in the Ferlo could also be explained by the intensity of grazing and the recurrence of bush fires [41]. These two factors constitute the major problem in the management of pastoral fodder resources in the Ferlo [41].

5. Conclusions

Initially, this study provided descriptive data that could be useful for the proper management and monitoring of the dynamics of woody stands in the Ferlo. The results of this study show that this flora is characterised by the abundance of a few species adapted to drought. However, the gradual increase in rainfall observed towards the end of the 1980s could help to rebalance this floristic composition by reducing the vulnerability of the mesophilous species inventoried in the woody stand.

The heterogeneity of the environment and the variability linked to the climate have visible influences on the distribution of the flora, in which the intertwined Sahelian and Sudanian floristic components that today make up the Fertile Ferlo are generally distinguished.

During reforestation operations, several species are planted without taking into account their edaphic preferences. This study shows that reforestation initiatives must take these factors into account to optimise the chances of success.

The lowlands, which offer more favourable conditions for the regeneration and development of woody plants, must be taken into account in strategies to rehabilitate the ecosystems of the Ferlo in the context of the Great Green Wall.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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