Journal of Agriculture and Environment for International Development - JAEID 2025, 119 (1): 19 - 42
DOI: 10.36253/jaeid-14871

Phytosociological study of herbaceous communities under *Vachellia tortilis* subsp. *raddiana* (Savi) Kyal. & Boatwr in eastern Niger

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Submitted on: 2023, 22 June; accepted on: 2025, 20 June. Section: Research Papers

Abstract: The present study was conducted in eastern Niger with the objective of assessing the floristic diversity under the canopy of *Vachellia tortilis*. To collect detailed data on the plant species present, the sigmatist method of abundance-dominance of Braun-Blanquet was employed, which is a common phytosociological technique for determining the relative abundance and dominance of species in each area. This method helps classify species based on their frequency and coverage. A total of 138 plots were surveyed to ensure a comprehensive representation of the study area. These plots were distributed across various locations under the canopy of *V. tortilis*, covering diverse topographies and environmental conditions. Hierarchical Ascending Classification (HAC) was used to group plant species based on their similarities in abundance and presence across the plots. Detrended Correspondence Analysis (DCA) helped visualize the distribution of plant species in relation to environmental gradients such as soil type and moisture content, ensuring that plant groupings were not solely influenced by environmental variables. Canonical Correspondence Analysis (CCA) was employed to further explore the relationships between plant species and environmental factors, providing a deeper understanding of how plant communities are structured and influenced by both biotic and abiotic factors. The results revealed 5 plant groupings with a total species richness of 35 herbaceous species divided into 19 families. The analysis of the floristic composition shows that the Poaceae family (41.08%) is the most important, followed by the Mimosaceae (14.82%). The analysis of diversity indices shows that the greatest specific diversity is observed in the *V. tortilis* and *Cenchrus biflorus* grouping (22 species) with a Shannon index of 2.96 and a Piélou equitability of 0.83. The dominance of Poaceae under the *V. tortilis* canopy suggests that this tree species influences herbaceous community composition by creating favorable ecological conditions such as soil moisture retention and light availability.

Keywords: Phytosociology, Herbaceous communities, Vachellia tortilis, Vegetation dynamics, Eastern Niger

Introduction

Sahelian ecosystems, characterized by their aridity, high climatic variability, and fragile balance, represent a major challenge for biodiversity conservation and the maintenance of essential ecosystem services (Thomas *et al*., 2018). These environments, crucial for the livelihoods of millions, face increasing pressures from climate change, including altered rainfall patterns and increased temperatures, as well as anthropogenic activities such as overgrazing, deforestation, and agricultural expansion (Prince *et al*., 2018). In Niger, these pressures lead to progressive vegetation degradation, soil erosion, and a significant loss of biodiversity, threatening the resilience of agropastoral systems and the well-being of local communities.

Understanding the complex interactions between plant species and their environment is therefore essential for developing effective conservation and management strategies. Phytosociological studies, which focus on the composition, structure, and distribution of plant communities, provide critical insights into the ecological dynamics of these ecosystems. In particular, the study of key species, such as *Vachellia tortilis* subsp. *raddiana* (formerly *Acacia tortilis* subsp. *raddiana*), is of paramount importance. This tree species plays a crucial role in structuring plant communities and modulating the ecological functions of Sahelian habitats through its influence on microclimate, soil properties, and resource availability (Danjouma *et al*., 2024).

Recent research has increasingly highlighted that the presence of trees in these ecosystems does not solely result in resource competition but also fosters facilitative interactions that are vital for ecosystem functioning and resilience. For instance, Danjouma *et al*. (2024) demonstrated in the central giraffe habitat zone in Niger that trees significantly influence the floristic diversity and spatial distribution of herbaceous species, creating heterogeneous habitats that support a wider range of plant life. Similarly, studies emphasize that tree cover enhances soil fertility through increased organic matter and nutrient inputs, improves water infiltration, and creates microclimates conducive to growth by providing shade and reducing evapotranspiration, thereby mitigating the impact of climatic extremes and boosting biomass production (Abdourhamane *et al*., 2013).

Analyzing the interactions beneath the canopy of *V. tortilis* subsp. *raddiana* allows for a better understanding of the dynamics of facilitation and competition that shape plant communities in Sahelian environments. This approach also provides an opportunity to identify indicator species of habitat quality, assess the impact of anthropogenic disturbances on biodiversity, and inform sustainable land management practices. Studies conducted in other Sahelian regions have confirmed that the presence of *V. tortilis* often promotes an increase in floristic richness and both above- and below-ground phytomass production under its canopy, highlighting its role as a nurse species (Oumata *et al*., 2020; Diouf *et al*., 2021).

The objective of this study is to evaluate the floristic diversity and succession under the canopy of *V. tortilis* subsp. *raddiana* and assess its impact on the diversity and composition of herbaceous species in arid ecosystems of eastern Niger. The central hypothesis is that the presence of *V. tortilis* subsp. *raddiana* positively influences the diversity and floristic composition of herbaceous species beneath its canopy compared to open areas.

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Methods

Study area

The present study was conducted in eastern Niger, specifically in the Goure Department and the Diffa Region (Figure 1). The Goure Department is located between 9°20' and 12°00' East longitude and 13°00' and 17°30' North latitude. The Diffa Region lies between 10°30' and 15°35' East longitude and 13°04' and 18°00' North latitude (CUD, 2016).

In Diffa, the average annual rainfall is 488 mm, while Goure receives approximately 420 mm. The average annual temperature is 27.9°C in Diffa and 27.4°C in Goure, with maximum temperatures reaching 40.82°C in May and minimum temperatures dropping to 11.59°C in January in Diffa. In Goure, the maximum temperature is 40.42°C in May, and the minimum is 11.59°C in January (National Meteorological Directorate of Niger, 2020).

The vegetation in this region consists of sparsely wooded steppes, predominantly thorny, interspersed with bush formations often found on rocky outcrops. A discontinuous and sparse herbaceous cover is present in the steppes, mainly composed of annual grasses that disappear during the dry season (CUD, 2016).

Vachellia tortilis, commonly known as the umbrella thorn, is a keystone species in these arid ecosystems. It plays a crucial role in the rangelands of the Diffa region by providing shade and forage for livestock. The dominant livestock in this area includes zebu cattle, goats, and sheep, all well-adapted to the harsh climatic conditions (Idrissa *et al.*, 2020). However, grazing intensity is particularly high due to pressure from both transhumant and sedentary herds. This overgrazing leads to soil degradation, a decline in plant species richness, and reduced ecological resilience of local ecosystems (Amadou *et al.*, 2018).

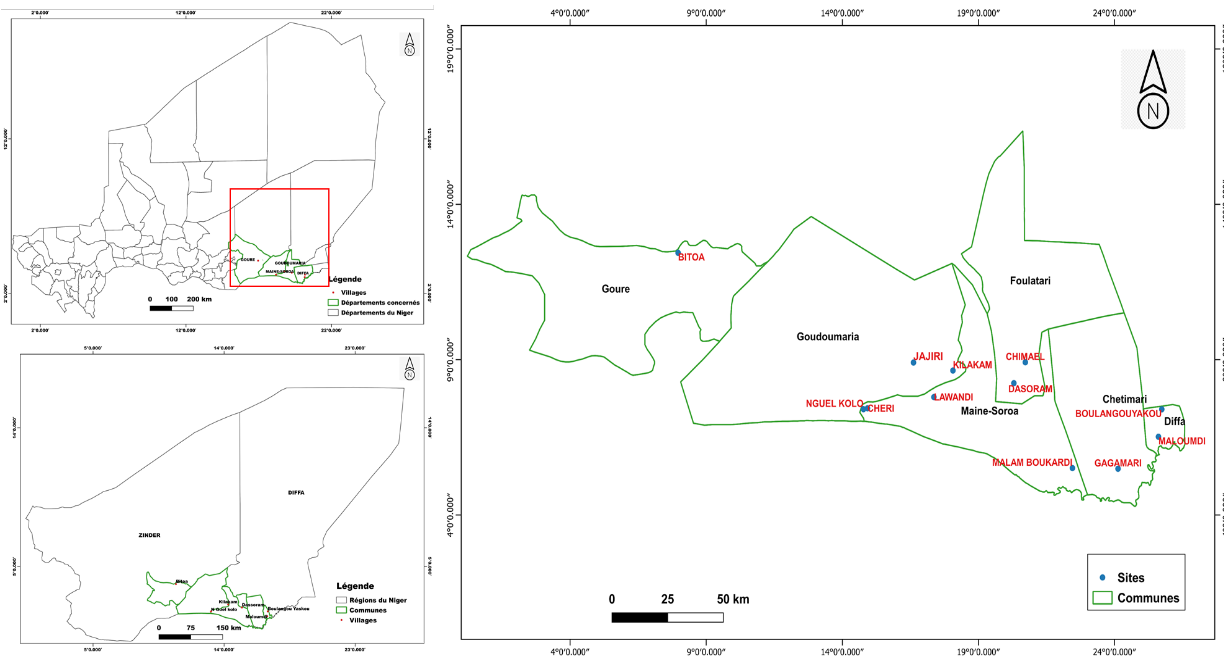


Figure 1: Study area in eastern Niger in 2017

Data collection

The study was conducted in the Gouré and Diffa regions of eastern Niger. Five study sites were selected: Bitoa, Cheri, Djajeri, Kilakam, and N'Guel Kolo. At each site, sampling was performed along four 3 km transects, resulting in a total of 200 plots (40 plots per site) (Figure 2). The plots were strategically positioned around individual *V. tortilis* trees to capture the spatial heterogeneity of the associated herbaceous communities.

A 1000 m² plot size (50 m x 20 m) was chosen, slightly larger than the 1000 m² plots (50 m x 20 m) used by Mahamane and Saadou (2008) in steppe formations. This adjustment was made to adequately encompass the area influenced by the tree canopy and its immediate surroundings. Within each plot, the presence, abundance, and cover of all herbaceous species were recorded. Additionally, tree parameters such as total height, diameter at breast height (DBH, 1.30 m above ground), and the lengths of two perpendicular crown axes were measured.

The modified Braun-Blanquet cover-abundance scale, as described by Braun-Blanquet (1932), was employed to assess the herbaceous vegetation beneath *V. tortilis* subsp. *raddiana* canopies. This adaptation addresses the unique characteristics of Sahelian herbaceous communities (Morou, 2010; Rabiou, 2016; Idrissa *et al.*, 2020) and aligns with recent protocols for arid ecosystems, ensuring accurate representation of low-cover species often prevalent in such environments (Müller *et al.*, 2022). For each plot, data on geomorphology (lowlands, dune slopes, dune flats) and soil texture (sandy, silty-clayey, silty-sandy) were collected. Given the arid nature of the study area, measuring organic matter was deemed unnecessary due to its minimal presence.

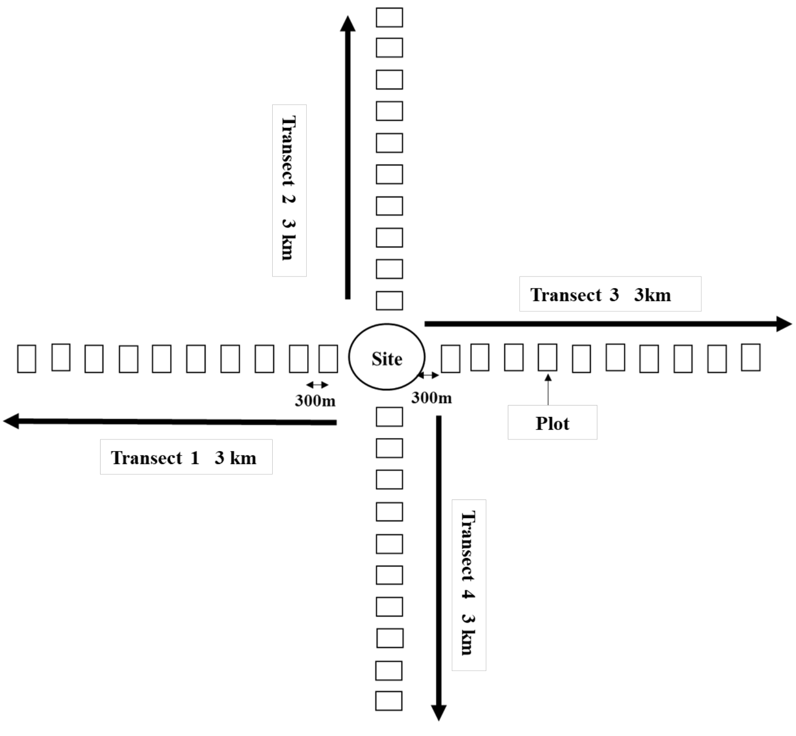


Figure 2: Floristic inventory device in eastern Niger in 2017

Data analysis

In each plot, average values for parameters such as height, diameter, number of stems, number of species, and cover were calculated exclusively for *Vachellia tortilis* plants. Welch's t-test was applied to compare the means, as the data did not follow a normal distribution, as determined by the Ryan-Joiner normality test. For the herbaceous layer, diversity indices and frequencies were calculated.

To identify distinct vegetation groups, a matrix of 200 records and 35 species was analyzed using non-metric multidimensional scaling (NMDS) with PCORD 5 software. NMDS ordination was employed to visualize relationships among samples based on species composition and abundance. Prior to clustering, data were transformed using a square root transformation to downweight the influence of highly abundant species. The resulting ordination was then subjected to Ascending Hierarchical Classification (AHC) to group samples. AHC was performed using Ward's linkage method and a similarity distance of 38%. This distance was chosen based on an examination of the dendrogram to identify a level of clustering that resulted in ecologically interpretable groups.

Indicator values for each plant community species were calculated using Indicator Species Analysis (ISA) in PCORD 5. ISA combines the relative abundance and relative frequency of a species within a group to calculate an indicator value. The statistical significance of indicator values was assessed using a Monte Carlo test with 1,000 permutations. Species with a P-value of less than 0.05 were considered significant indicator species for that grouping, indicating that their presence and abundance were significantly associated with that particular vegetation group and not likely due to chance.

To study the relationship between plant groupings and environmental parameters (soil texture and site geomorphology), a Canonical Correspondence Analysis (CCA) was conducted using the "vegan" package in R (version 4.2.2) through RStudio (version 2024.12.0). Direct gradient analysis was used to test the effect of each environmental variable on species distribution, employing the Monte Carlo permutation test as outlined by Alhassane *et al*. (2017).

Floristic diversity

Two types of indices were calculated: alpha diversity and beta diversity. These indices are fundamental tools for exploring the richness and complexity of ecosystems at different scales (Whittaker, 1960). They are complementary; alpha diversity focuses on the diversity within a specific site (local diversity), while beta diversity highlights differences between sites and explains how this local diversity contributes to the total diversity of a region (gamma diversity).

Species richness (S) is defined as the number of species that a community (G1, G2, G3, G4, and G5) contains. The Shannon index (H') is calculated by the following formula: $H = -\sum_{i=1}^{s} P_i \log_2 P_i$ with s representing the total number of species; $P_i = (n_i / N)$ representing the relative proportion of the average cover of species i in the community; n_i representing the average cover of species i; and N representing the total cover of all species (Shannon, 1949). Piélou equitability (E) is calculated by the following formula: $E = \frac{H'}{\log_2 S}$ (Pielou, 1966). Sorensen's community index (Is) (1948) is calculated according to the formula below: $Is = \frac{2c}{(a+b)}$ (Sorensen, 1948) with a representing the number of species of A; b representing the number of species of B; c representing the number of species common to A and B; and A and B representing the plant communities being compared.

Results

Group delineation using Detrended Correspondence Analysis (DCA)

Figure 3 shows a partition of these 138 plots into 5 groups individualized according to their similarity in the plane formed by axes 1 and 2. The plant groupings thus formed are made up of several records with 14 plots for the grouping (G1), 36 plots for the grouping (G2), 23 plots for the grouping (G3), 70 plots for the grouping (G4), and 9 plots for the grouping (G5).

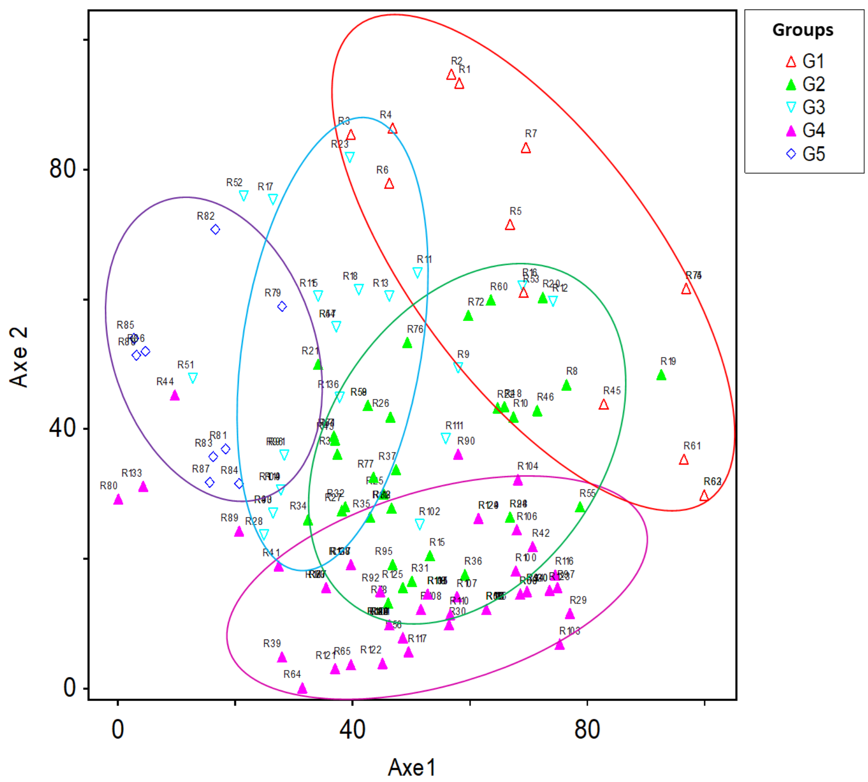
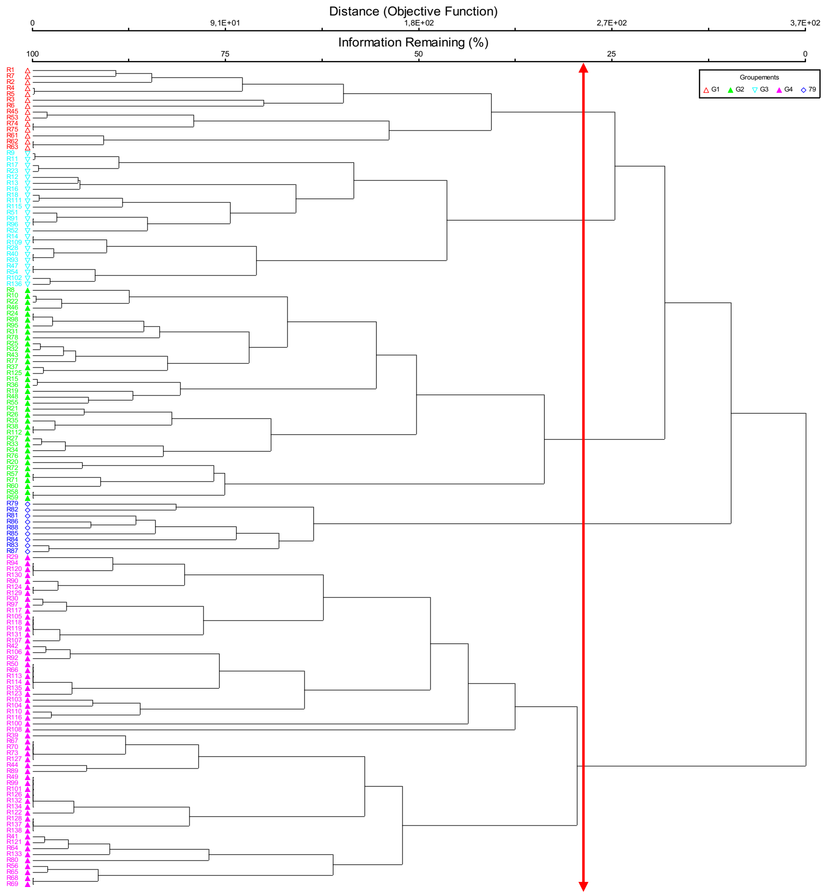


Figure 3: Distribution of multidimensional positioning surveys (NMDS) in eastern Niger in 2017

The dendrogram resulting from the Ascending Hierarchical Classification (AHC) (Figure 4) facilitated the identification of five distinct plant groups beneath the canopy of *Vachellia tortilis* subsp. *raddiana*. A similarity threshold of 38% was selected based on visual inspection of the dendrogram, which clearly delineated these clusters into five ecologically meaningful groups. These are the groups with *V. tortilis* subsp. *raddiana* and *Chloris prieurii* (G1), the grouping with *V. tortilis* subsp. *raddiana* and *Gisekia pharnacioides* (G2), the grouping with *V. tortilis* subsp. *raddiana* and *Schoenefeldia gracilis* (G3), the grouping with *V. tortilis* subsp. *raddiana* and *Peristrophe bicalyculata* (G4), and the grouping with *V. tortilis* subsp. *raddiana* and *Cenchrus biflorus* (G5). Group characteristics are shown in Table 1.



Legend: Group G1: *Vachellia tortilis and Chloris pieurii*; **Group G2:** *Vachellia tortilis* and *Panicum anabaptistum*; **Group G3:** *Vachellia tortilis* and *Schoenefeldia gracilis*; **Group G4:** *Vachellia tortilis* and *Pennisetum pedicellatum* and **Group G5:** *Vachellia tortilis* and *Cenchrus biflorus.*

Figure 4: Ascending Hierarchical Classification (AHC) of plant groups in eastern Niger in 2017

Table 1. Group characteristics in eastern Niger in 2017

GROUPS	G1	G2	G3	G4	G5
Number of surveys	14	36	23	70	9
Number of species recorded under canopy	7	6	2	4	12
Average number of species per survey	3.57±21	3.48±0.73	4.25±1	5.75±1.39	3.44±1.17
Species					
Chloris pieurii Kunth	1	-	-	-	-
Spermacoce stachydea DC	1	-	-	-	-
Dactyloctenium aegyptium (L.) Willd.	1	-	-	-	-
Digitaria horizontalis Willd.	1	-	-	-	-
Jacquemontia tamnifolia (L.) Griseb.	1	-	-	-	-
Phyllanthus pentandrus Schum. et Thonn.	1	-	-	-	-
Tribulus terrestris L.	1	-	-	-	-
Gisekia pharnacioides L.	-	1	-	-	-
Aerva javanica (Burm.) Juss. ex Schult.	-	1	-	-	-
Amaranthus viridis L.	-	1	-	-	-
Corchorus tridens L.	-	1	-	-	-
Maerua angolensis DC.	-	1	-	-	-
Panicum anabaptistum Steud.	-	1	-	-	-
Schoenefeldia gracilis Kunth	-	-	1	-	-
Merremia pinnata (Choisy.) f.	-	-	1	-	-
Peristrophe bicalyculata (Retz.) Nees	-	-	-	1	-
Gynandropsis gynandra (L.)	-	-	-	1	-
Momordica balsamina L.	-	-	-	1	-
Pennisetum pedicellatum Trin.	-	-	-	1	-
Ipomoea coptica (L.) Roth. ex. Roem. et Schult	-	-	-		1
Alysicarpus ovalifolius (Schum. Et Thonn.) J. Léonard	-	-	-		1
Cenchrus biflorus Roxb.	-	-	-		1
Chrozophora bracchiana Vis	-	-	-		1
Citrillus lanatus (Thunb.) Matsumara et Nakai	-	-	-		1
Commelina benghalensis L.	-	-	-		1
Cucumis melo Naud	-	-	-		1
Echinochloa colona (L.) Link	-	-	-		1
Ficus ingens (Miq.) Miq	-	-	-		1
Leucas martinicensis (Jacq.) R. Br.	-	-	-		1
Mollugo nudicaulis Lam.	-	-	-		1
Pergularia tomentosa L	-	-	-		1

Structural characteristics of plant groups

Table 2 presents the statistical comparison of various parameters across five groups (G1 to G5), including the average values, F-statistics, and p-values for each parameter. For the number of species, the average values range from 3.44 in G5 to 5.75 in G4. The F-statistic is 7.77, with a p-value of 0.0002, indicating that the number of species differs significantly between the groups. Regarding the number of stems, the average values vary from 1.35 in G2 to 1.90 in G5. The F-statistic is 2.50, and the p-value is 0.0585, suggesting that the difference in the number of stems across the groups is not statistically significant at the 0.05 significance level. For the diameter, the average values range from 13.08 cm in G1 to 22.12 cm in G3. The F-statistic is 4.58, with a p-value of 0.005, indicating a significant difference in diameter between the groups.

In terms of height, the average values range from 4.99 m in G1 to 6.30 m in G3. The F-statistic is 3.94, and the p-value is 0.010, suggesting that the height significantly differs between the groups. Finally, for coverage, the average values range from 25.90 m^2 in G1 to 43.50 m^2 in G2. The F-statistic is 2.98, and the p-value is 0.031, indicating a significant difference in coverage between the groups.

Table 2. Dendrometric parameters of V. tortilis plants and number of herbaceous species in eastern Niger in 2017

Parameters	Groups	Average	F-statistic	P-value
Number of species	G1	3.57±2.10	7.77	0.0002
	G2	3.48±0.73		
	G3	4.25±1.00		
	G4	5.75±1.39		
	G5	3.44±1.17		
Number of stems	G1	1.36±0.50	2.50	0.0585
	G2	1.35±0.71		
	G3	1.64±0.93		
	G4	1.50±0.54		
	G5	1.90±1.05		
Diameter (cm)	G1	13.08±6.02	4.58	0.005
	G2	20.30±12.81		
	G3	22.12±8.87		
	G4	17.22±11.03		
	G5	16.44±7.93		
Height (m)	G1	4.99±1.26	3.94	0.010
	G2	5.60±1.18		
	G3	6.30±1.32		
	G4	5.21±1.13		
	G5	5.31±1.45		
Coverage (m^2)	G1	25.90±18.81	2.98	0.031
	G2	43.50±22.00		
	G3	40.72±28.42		
	G4	26.05±13.32		
	G5	42.11±28.35		

Legend: G: *Group;* ***Group G1:*** *V. tortilis and C. pieurii;* ***Group G2:*** *V. tortilis and G. pharnacioides;* ***Group G3:*** *V. tortilis and S. gracilis;* ***Group G4:*** *V. tortilis and P. pedicellatum;* ***Group G5:*** *V. tortilis and P. bicalyculata.*

Species composition of plant groups

Table 1 presents a comparative analysis of the five groups (G1 to G5) in terms of species diversity and their presence in each group. The number of surveys varies significantly between the groups, ranging from 9 for G5 to 70 for G4. The total number of species recorded under the canopy also varies, ranging from 2 for G3 to 12 for G5. Regarding the average number of species per survey, group G4 has the highest number (5.75 ± 1.39), while G2 has the lowest average (3.48 ± 0.73).

In terms of species presence, group G1 stands out with seven unique species, including *Chloris pieurii*, *Spermacoce stachydea*, and *Tribulus terrestris*. Group G2, on the other hand, includes six unique species, such as *G. pharnacioides* and *Panicum anabaptistum*. Group G3, with only two unique species (*S. gracilis* and *Merremia pinnata*), has the lowest diversity. Group G4, which contains four unique species like *P. bicalyculata* and *P. pedicellatum*, shows more moderate diversity. Finally, group G5 is the most diverse, with 12 unique species, such as *Ipomoea coptica* and *Ficus ingens*, representing a broader variety of species in this table.

Figure 5 illustrates the distribution of herbaceous species families under the cover of *V. tortilis*, with a total of 19 families recorded. The most prominent families include Poaceae (41.08%), followed by Mimosaceae (14.82%), Acanthaceae (11.06%), and Aizoaceae (10.31%). These percentages reflect the relative frequency of each family, which is calculated based on the number of occurrences of each family across all plots. Among the species, *P. pedicellatum* (10.21%), *P. bicalyculata* (6.91%), and *Alysicarpus ovalifolius* (4.1%) are the most represented in terms of cover rates, as shown in Figure 6. However, the method used to determine these cover rates should be specified to ensure clarity and replicability of the data.

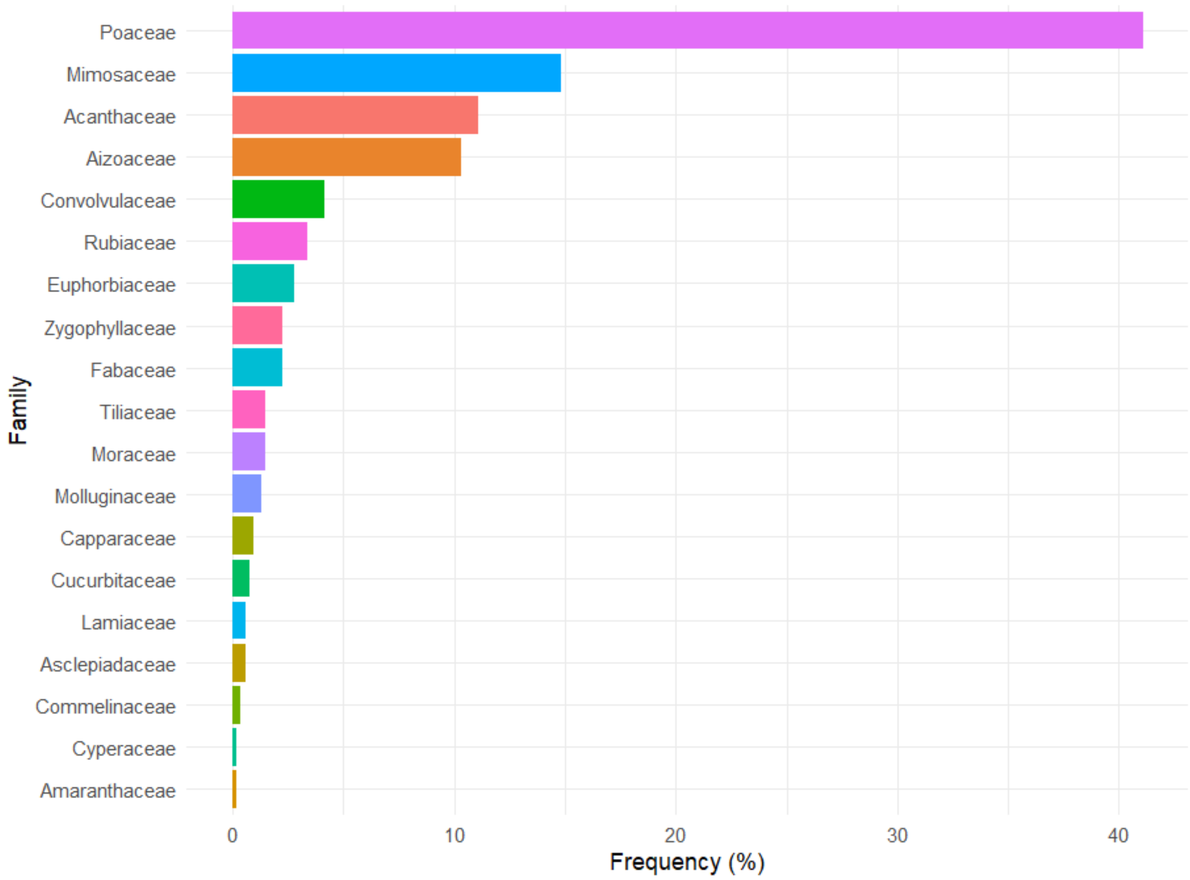


Figure 5: Overall average family recovery in eastern Niger in 2017

Figure 6 illustrates the average percentage cover of fourteen plant species distributed across five distinct groups (G1 to G5), highlighting variations in the structure and composition of plant communities in the study area. Some species stand out due to their high cover in specific groups. *P. pedicellatum* clearly dominates groups G1 and G2, suggesting a particular adaptation to the ecological conditions of these environments. Similarly, *E. colona* and *C. biflorus* exhibit significant cover in group G4. Although *Digitaria horizontalis* is present in G1, it shows a more moderate cover compared to *P.*

DOI: 10.36253/jaeid-14871

pedicellatum. Other species, such as *Zornia glochidiata*, *S. gracilis*, and *P. bicalyculata*, display lower cover and are less represented across all groups. Moreover, since *P. pedicellatum* occurs in two groups, it is likely more frequent than *E. colona* and *C. biflorus*, which are concentrated solely in group G4.

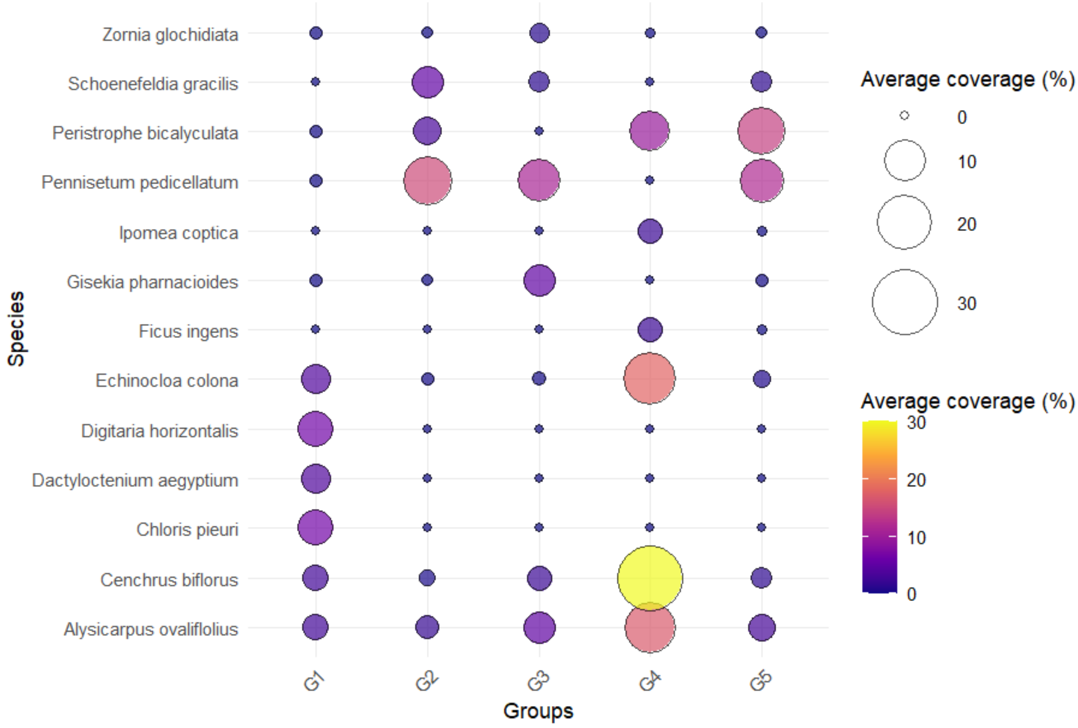


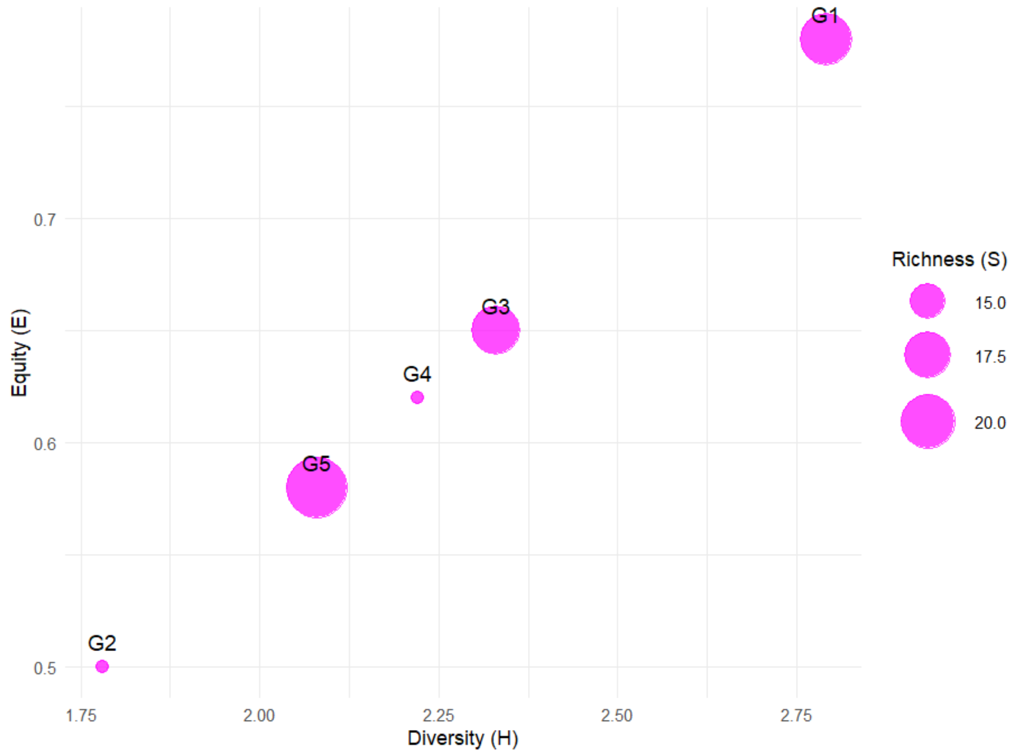
Figure 6: Overall species coverage in eastern Niger in 2017

Figure 7 is a photograph that visually illustrates the herbaceous vegetation growing beneath the canopy of *a Vachellia tortilis* tree in eastern Niger in 2017. It complements the data on mean vegetation cover of the species presented in Figure 6, providing a concrete example of the environment under study.

Figure 7: Herbaceous under a Vachellia tortilis canopy in eastern Niger in 2017

Diversity indices of plant groups

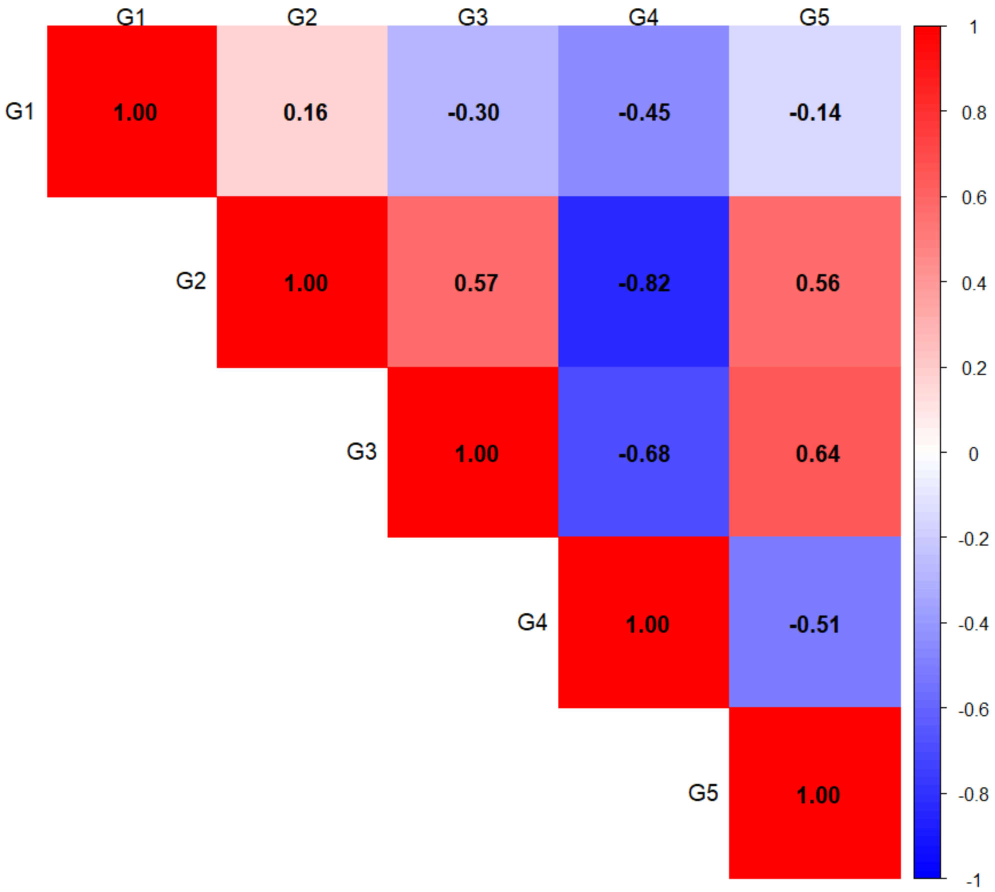
Figure 8 illustrates the relationship between species diversity (H) and evenness (E) across five groups (G1 to G5), with species richness (S) represented by bubble size. Group G1 stands out with the highest values of diversity (H = 2.75), evenness (E = 0.78), and species richness (S = 20), indicating a rich and well-balanced plant community. In contrast, Group G2 exhibits the lowest values (H = 1.75, E = 0.50, S = 15), suggesting a dominance of a few species and reduced diversity. Groups G3 (H = 2.30, E = 0.65, S = 18) and G4 (H = 2.20, E = 0.62, S = 16) occupy an intermediate position, showing moderate levels of diversity and evenness. Finally, Group G5 (H = 2.05, E = 0.58, S = 17) exhibits moderate species richness but a less homogeneous distribution of abundances.



Legend: Group G1: *V. tortilis and C. pieurii*; **Group G2:** *V. tortilis* and *P. anabaptistum*; **Group G3:** *V. tortilis* and *S. gracilis*; **Group G4:** *V. tortilis* and *P. pedicellatum* and **Group G5:** *V. tortilis* and *C. biflorus.*

Figure 8: Variation in Equitability (E), Species Richness (S), and Diversity (H) across ecological groups

The analysis of the correlation heatmap and Sorensen similarity coefficients reveals complex relationships between the five studied groups (G1 to G5) (Figure 9). The Sorensen coefficients, ranging from 38% to 75%, indicate moderate to high similarity between the groups. This observation is supported by the positive correlations (red) in the heatmap, particularly between groups G2 and G3, G2 and G5, and G3 and G5, which also show relatively high Sorensen coefficients. Groups G3 and G5, as well as G2 and G5, stand out with the highest Sorensen coefficients (75%) and strong positive correlations. On the other hand, groups G3 and G4, as well as G2 and G4, exhibit the lowest Sorensen coefficients (38%) and strong negative correlations (blue).



Legend: Group G1: *V. tortilis and C. pieurii*; **Group G2:** *V. tortilis* and *P. anabaptistum*; **Group G3:** *V. tortilis* and *S. gracilis*; **Group G4:** *V. tortilis* and *P. pedicellatum* and **Group G5:** *V. tortilis* and *C. biflorus*.

Figure 9: Correlation matrix between plant groups

Influence of environmental variables on plant group distribution

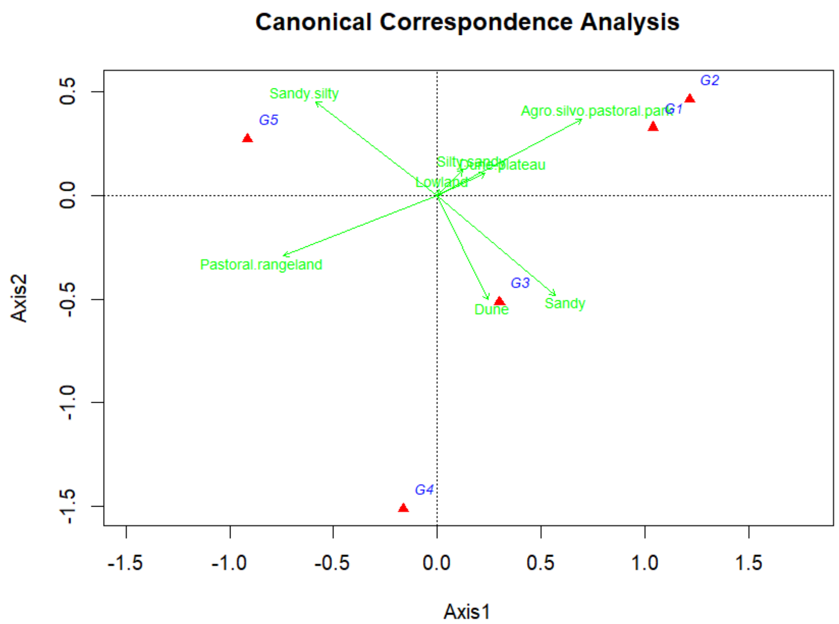
The analysis of the environmental variables table tests the influence of several environmental factors on the studied groups (Table 5). The results are presented in terms of ChiSquare, F, and Pr(>F), with Pr(>F) indicating the statistical significance of the variables. Among the significant environmental variables, Sandy is highly significant ($p < 0.001$), indicating that it has a strong influence on the distribution of the studied groups. Similarly, Pastoral.rangeland shows a comparable statistical significance ($p < 0.001$). The variable Agro.silvo.pastoral.park is also significant ($p < 0.01$). Dune, with a p-value less than 0.001, also demonstrates a significant influence. As for Silty.sandy, although it is significant at a moderate level ($p < 0.05$), its impact is less pronounced compared to the other variables. In contrast, several variables do not show statistically significant influence, such as Sandy.silty ($p = 1.000$), which has no role in the distribution of the groups. Dune plateau and Lowland also show non-significant results, although Lowland is marginally significant with a p-value close to 0.070, suggesting a limited influence but not enough to be considered a major factor.

Table 3: Environmental variables test

ENVIRONMENTAL VARIABLES	DF	CHISQUARE	F	PR(>F)
Sandy	1	0.40293	18.1817	0.001 ***
Silty.sandy	1	0.05917	2.6701	0.041 *
Sandy.silty	1	0.00000	0.0000	1.000
Pastoral.rangeland	1	0.40212	18.1452	0.001 ***
Agro.silvo.pastoral.park	1	0.09713	4.3826	0.002 **
Dune	1	0.11818	5.3326	0.001 ***
Dune.plateau	1	0.01282	0.5783	0.701
Lowland	1	0.04883	2.2036	0.070

*Signif. codes : 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

The CCA reveals that environmental variables significantly influence the distribution of plant groups (G1, G2, G3, G4, and G5) as shown in figure 10. This suggests that environmental conditions play a key role in shaping the composition and distribution of plant communities. The CCA ordination depicted in figure 10 visualizes the distribution of herbaceous species and the five plant groups in relation to environmental variables. The groups G1 to G5 are represented as triangular red points in the figure.



Legend: Groups: G1: *Vachellia tortilis and Chloris pieurii*; **G2:** *Vachellia tortilis* and *Panicum anabaptistum*; **G3:** *Vachellia tortilis* and *Schoenefeldia gracilis*; **G4:** *Vachellia tortilis* and *Pennisetum pedicellatum* and **G5:** *Vachellia tortilis* and *Cenchrus biflorus.*

Figure 10: Factorial design of the Correspondence Analysis (CA) in eastern Niger in 2017

The first two axes (Axis 1 and Axis 2) account for the majority of the variance in the data, meaning they capture the primary environmental gradients that affect the distribution of the plant groups. Tables 4 and 5 provide additional details on the variance explained by each axis and the statistical significance of the environmental variables. Axis 1 is closely linked to the variables "Sandy" (sandy soils) and "Pastoral rangeland" (pastures), emphasizing their pivotal role in determining the distribution of plant groups. This indicates that both soil types and land management practices significantly influence the composition of plant communities.

Table 3. Accumulated constrained eigenvalues

STATISTIC	AXIS1	AXIS2	AXIS3	AXIS4
Eigenvalue	0.7259	0.2785	0.10666	0.03012
Proportion Explained	0.6361	0.2441	0.09347	0.02639
Cumulative Proport	0.6361	0.8801	0.97361	1.00000

Table 4. Significance test by axis

Axis	Df	ChiSquare	F	Pr(>F)
Axis1	1	0.72586	33.7689	0.001 ***
Axis2	1	0.27854	12.9584	0.001 ***
Axis3	1	0.10666	4.9623	0.206
Axis4	1	0.03012	1.4010	0.996

*Signif. codes : 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Discussion

Group delineation using Detrended Correspondence Analysis (DCA)

Our analysis of the floristic surveys revealed five distinct plant groups, each reflecting notable variations in species composition beneath the *V. tortilis* canopy. The dendrogram (Figure 4) shows that, while there is a degree of overall homogeneity in the plant associations, significant differences in community composition justify the separation into five groups using a 38% similarity threshold. This threshold indicates that although the groups share some common species, each group exhibits unique floristic characteristics that define distinct microhabitats.

The spatial partitioning observed in Figure 3 is consistent with previous findings (Diallo *et al*., 2015; Ndiaye *et al*., 2014), which reported that herbaceous communities especially those dominated by Poaceae tend to prevail under tree canopies. Recent studies by Johnson *et al*. (2017) and Martinez *et al*. (2021) further support these trends by emphasizing that canopy-induced modifications create distinct ecological niches. These modifications occur through changes in soil moisture, increased organic matter inputs from litterfall, and improved microclimatic regulation, all of which contribute to a mosaic of microhabitats beneath the canopy (Johnson *et al*., 2017; Martinez *et al*., 2021).

For instance, our results indicate that Group G4, which included the highest number of surveys (70), exhibited elevated species richness, greater herbaceous cover, and improved soil moisture conditions. This suggests that the microhabitat conditions in this group are optimal for herbaceous species development a pattern also noted by recent investigations in semi-arid ecosystems (Thompson *et al*., 2018). Conversely, Group G5, with only 9 surveys, displayed lower species diversity and reduced cover, indicating more restrictive environmental conditions, likely due to drier soils and less favorable microclimatic conditions. These ecological patterns underscore the critical role of *V. tortilis* in locally modifying ecological conditions by creating “islands of fertility” that enhance habitat suitability. Such insights are crucial for understanding tree-grass interactions and can inform sustainable management practices in semi-arid environments (Martinez *et al*., 2021; Thompson *et al*., 2018).

Structural characteristics of plant groups

Our analysis of structural parameters (Table 2) reveals significant differences among plant groups in several key aspects, including species number, tree diameter, height, and canopy coverage. These differences suggest that environmental influences vary considerably across sites, affecting both tree structure and the associated herbaceous communities.

First, the number of species recorded under the canopy varied significantly among groups ($F = 7.77$, $p = 0.0002$). Notably, Group G4 exhibited the highest average number of species per survey (5.75 ± 1.39), while Group G5 had the lowest (3.44 ± 1.17). This variation implies that microhabitat conditions likely influenced by soil moisture, nutrient availability, and canopy density are more favorable in some areas (Group G4) than in others (Group G5). Recent work by Johnson *et al*. (2017) has shown that tree canopies can create “fertility islands” that support higher species richness, a phenomenon that corresponds well with our findings in Group G4.

In addition to species number, tree diameter and height also differed significantly between groups. For instance, Group G3 demonstrated the largest average diameter (22.12 ± 8.87 cm) and height (6.30 ± 1.32 m), while Group G1 had the smallest average values (13.08 ± 6.02 cm in diameter and 4.99 ± 1.26 m in height). These structural differences likely reflect variations in tree age, growth conditions, and resource competition. Martinez *et al*. (2021) found that trees in more favorable microhabitats tend to grow larger due to enhanced water and nutrient availability, a trend that is evident in our results.

Moreover, canopy coverage varied significantly among the groups ($F = 2.98$, $p = 0.031$). Group G2, with an average canopy coverage of 43.50 ± 22.00 m^2, exhibited the densest canopy. A denser canopy can modify the underlying microclimate by reducing evaporation and moderating soil temperature, thereby promoting greater moisture retention in the understory. Thompson *et al*. (2018) reported that in semi-arid landscapes, such denser canopies enhance understory moisture retention and, consequently, contribute to higher plant diversity. This mechanism likely underlies the observed differences in species diversity among the groups.

Species composition of plant groups

The investigation into the *V. tortilis* population has provided insights into its influence on the surrounding herbaceous vegetation. As shown in Table 1, the average number of species per plot varied among groups, with Group G4 exhibiting the highest mean (5.75 ± 1.39) and Group G2 the lowest (3.48 ± 0.73). These figures are notably lower than the 16.4 species per plot reported by Akpo and Grouzis (2009) in Senegal, indicating a relatively impoverished herbaceous community under *V. tortilis* in our study area. Similar patterns have been documented by Bio *et al*. (2021) and Diallo *et al*. (2018), suggesting that factors such as limited rainfall, specific soil characteristics, and intense grazing pressure may constrain species richness.

The relatively low plant cover (39.40 ± 2.75 m²) observed in our study, compared to the 50.24 m² reported by Akpo and Grouzis (1993), may further contribute to the reduced species diversity under the canopy. Yadeta *et al*. (2018) found that *V. tortilis* canopies significantly enhance soil nutrients and moisture, which could promote herbaceous biomass. However, they also noted that species richness remained similar under and outside the canopy, with a decline under increased grazing pressure. This suggests that while *V. tortilis* may improve certain soil conditions, other factors, such as grazing intensity, play a critical role in determining species diversity. Garg *et al*. (2021) observed that tree canopies in semi-arid forests positively influenced soil physico-chemical properties but negatively affected herbaceous species composition, diversity, and biomass due to reduced solar radiation reaching the understory. This finding implies that the shading effect of *V. tortilis* could limit the growth of certain herbaceous species, thereby reducing overall diversity.

Additionally, research has shown that soil nitrogen content inversely affects species richness, suggesting that increased nitrogen levels under tree canopies might lead to reduced herbaceous diversity. For instance, Konaré *et al*. (2021) demonstrated that trees in humid savannas stimulate nitrification beneath their canopies, leading to nitrogen enrichment in the soil. This nitrogen accumulation can alter the competitive dynamics among herbaceous species, potentially favoring nitrogen-tolerant species and suppressing others, thereby reducing overall species richness.

Diversity indices of plant groups

The study of floristic diversity under the canopy of *V. tortilis* highlights significant variations in species composition, diversity, and richness across different groups. The dominance of Poaceae, followed by Mimosaceae and Acanthaceae, aligns with previous findings by Diallo *et al*. (2015), Ndiaye *et al*. (2014), and Diallo *et al*. (2018) in Senegal. The prevalence of Poaceae can be attributed to their high regrowth capacity, their adaptability to varying environmental conditions, and their ability to take advantage of improved soil fertility under tree canopies. This observation is consistent with studies by Belsky *et al*. (1993) and Ludwig *et al*. (2004), who demonstrated that trees in arid and semi-arid regions create "fertility islands" that promote herbaceous growth by enhancing nutrient availability.

The analysis of diversity and equity indicators, as shown in Figure 5, reveals that floristic diversity varies significantly between groups. Group G1 exhibits the highest diversity (H = 2.75) and equity (E = 0.75), indicating a more balanced distribution of species within this group. This suggests that environmental conditions, likely influenced by the tree canopy, promote species coexistence and reduce competitive exclusion. In contrast, Group G2, which has the lowest diversity (H = 1.75) and equity (E = 0.50), may be subject to higher dominance by certain species, limiting the establishment of other taxa. The observed patterns align with findings by Weltzin and Coughenour (1990), who noted that *V. tortilis* can significantly alter species composition by modifying soil conditions, light availability, and moisture retention. Trees can facilitate or inhibit herbaceous growth depending on canopy density, soil compaction, and grazing pressure (Sileshi, 2016).

The correlation heatmap (Figure 6) provides additional insights into the relationships between groups. The strong negative correlation between G2 and G4 (r = -0.82) suggests distinct ecological conditions, possibly related to variations in soil fertility, moisture availability, or grazing impact. This pattern is in line with the findings of Scholes and Archer (1997), who reported that differences in resource availability under tree canopies versus open areas create distinct microhabitats, influencing species composition. The positive correlation between G2 and G3 ($r = 0.57$) indicates some degree of similarity in species assemblages, which could be driven by comparable levels of disturbance or grazing intensity. Grazing has been recognized as a key driver of species distribution in savanna ecosystems (Oba *et al*., 2000), and its effects should be considered in the interpretation of these results.

The role of *V. tortilis* in structuring herbaceous vegetation is well documented in arid and semi-arid environments. Several studies (Diallo *et al*., 2006; Remigi *et al*., 2008; Akpo and Grouzis, 2009) have highlighted the capacity of this species to improve soil properties through organic matter accumulation and nutrient cycling. Our results suggest that the presence of *V. tortilis* enhances floristic richness in certain groups, particularly G1 and G5, where species richness ($S = 20$) is higher. This supports the hypothesis that tree canopies create favorable microhabitats for understory vegetation, as reported by Ludwig *et al*. (2004) and Dohn *et al*. (2013). However, the relatively low plant cover (39.40 ± 2.75 m²) observed in our study, compared to the 50.24 m² reported by Akpo and Grouzis (1993), suggests that additional limiting factors, such as low rainfall, soil compaction, and overgrazing, may be affecting vegetation development.

Floristic composition under *V. tortilis* can also be influenced by competition for resources. The dominance of *P. pedicellatum* in G1 and G2 suggests that these areas may experience moderate levels of tree-facilitated fertility, allowing certain fast-growing grasses to thrive. Conversely, the presence of *E. colona* and *C. biflorus* in G4 suggests a different ecological niche, potentially shaped by higher moisture availability or disturbance regimes. These findings are in agreement with the work of Walker *et al*. (1981), who described how herbaceous composition in savannas is driven by a combination of soil nutrients, light availability, and disturbance patterns. The influence of trees on microclimate conditions, particularly through shading and evapotranspiration reduction, is another key factor affecting floristic diversity, as demonstrated by Belsky *et al*. (1993).

Influence of environmental variables on plant group distribution

The distribution of plant communities under *V. tortilis* canopies in eastern Niger is strongly influenced by environmental factors, as demonstrated by Canonical Correspondence Analysis (CCA). The prominence of sandy soils ("Sandy") and pastoral rangelands ("Pastoral.rangeland") as key drivers ($p < 0.001$) confirms ecological principles governing arid ecosystems. Sandy soils, characterized by rapid drainage and low nutrient retention (Lee & Kim, 2019), favor drought-resistant species such as *C. biflorus* and *S. gracilis*. These species exhibit specific adaptations, such as deep root systems and C4 photosynthesis (Patel *et al*., 2020), optimizing their survival in nutrient-poor, water-limited environments.

The influence of pastoral rangelands highlights the long-term impact of grazing pressure, which selectively favors resilient grasses, such as *P. pedicellatum*, while suppressing less tolerant species. This pattern aligns with herbivory-driven succession observed in Sahelian ecosystems, as reported by Hiernaux *et al*. (2016).

The influence of agro-silvo-pastoral parks ("Agro.silvo.pastoral.park") and dune habitats ("Dune") further emphasizes the role of land management and topography in shaping plant communities. Agro-silvo-pastoral systems create heterogeneous microenvironments by integrating tree cover with agricultural and livestock activities, fostering niches for both ruderal species (*G. pharnacioides*) and nitrogen-fixing legumes (*A. ovalifolius*) (Bayala *et al*., 2021). Dune habitats, with their mobile substrates and limited moisture, favor psammophytic species such as *Z. glochidiata*, whose sand-binding root systems stabilize microsites (Trabucco *et al*., 2023). The absence of significant effects from "Sandy.silty" and "Dune.plateau" may reflect insufficient ecological contrast under *V. tortilis* canopies, where tree-mediated soil enrichment tends to homogenize edaphic conditions (Bernhard-Reversat, 1982). This suggests that, under these canopies, edaphic variations are less pronounced and may be masked by the trees' soil-modifying effects.

The marginal significance of lowland areas ("Lowland", p = 0.070) suggests localized moisture accumulation, although this effect may be obscured by the region's general aridity. This finding aligns with Martinez *et al*. (2021), who noted that microtopographic variations in Sahelian systems often result in subtle floristic differences detectable only through high-resolution sampling. Overall, the complex interplay of soil texture, land use, and microclimate supports the "mosaic theory" of arid ecosystems (Johnson *et al*., 2021), where tree canopies act as nuclei for resource redistribution, creating patches of enhanced biodiversity amidst broader environmental stressors.

Vachellia tortilis subsp. *raddiana* serves as a keystone species in Niger's Sahel, enhancing herbaceous biodiversity by creating microhabitats beneath its canopy. The species' preference for sandy soils and its role in pastoral systems promote the growth of drought-resistant grasses like *P. pedicellatum* and nitrogen-fixing legumes such as *A. ovalifolius*. Agro-silvo-pastoral practices and dune landscapes further increase habitat diversity. Variations in species richness and evenness among plant groups are influenced by niche differentiation and environmental filtering, with *V. tortilis* modifying soil conditions to mitigate aridity. To strengthen ecosystem resilience, it is essential to maintain tree density and adopt sustainable land management practices. Future studies should focus on seasonal variations and functional traits to inform conservation efforts, providing practical solutions to address climate change and human-induced challenges in Sahelian ecosystems.

Conflict of interest

The authors have declared no conflict of interest.

Data Availability Statement

Raw data are available on demand.

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