

Land use patterns drive demographic collapse and reveal urgent conservation needs of *Balanites aegyptiaca* (L.) Delile Stands in resilient dryland forests

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Abstract

Land-use intensity is a major determinant of structural vulnerability in dryland ecosystems, posing a threat to resilient multipurpose tree species globally. We investigated how specific land-use patterns affect the stand structure and dynamics of *Balanites aegyptiaca*, a keystone species for the Great Green Wall Initiative, across the Lake Chad Basin. Using dendrometric surveys (200 plots) and Factor Analysis of Mixed Data (FAMD), we characterized population attributes across different soil types and land-use systems (rangelands, cultivated fields). The stands exhibited a low average density (4.02 ± 2.7 stems ha⁻¹) and an inverted J-shaped diameter distribution, dominated by young individuals (DBH 10-50 cm). This structure indicates high post-recruitment mortality, resulting in a scarcity of mature trees (≥ 40 cm) and vulnerability to demographic collapse. FAMD results showed that the first factorial axis (16.9% of variance) primarily separates lightly exploited sandy soils from intensely cultivated loamy soils. This confirms that land-use patterns emerge as the key driver of the spatial organization and structural degradation of *B. aegyptiaca* populations. Our findings provide a scientific basis for urgent management strategies, emphasizing the need to mitigate intensive land-use impacts on adult cohorts to ensure the long-term sustainability of this vital resource in the Sahelian context.

Keywords: *Balanites aegyptiaca*, Lake Chad, Structure, Density, Sahel.

Introduction

Balanites aegyptiaca (L.) Delile, commonly known as the desert date, is a crucial multipurpose tree species widely distributed across the African Sahelian and Sudano-Sahelian zones, extending into the Middle East and South Asia (Sagna et al., 2014; Tesfaye, 2015; Murthy et al., 2021; Arbonnier, 2000; Hall & Walker, 1991). The species is highly valued for its exceptional wide ecological amplitude and its strong resistance to drought (Sagna et al., 2014; Tesfaye, 2015; Ousmane et al., 2023; Arbonnier, 2000), thriving across diverse soil types including sand, clay, and loams (Massaoudou et al., 2022; Sagna et al., 2014; Hall & Walker, 1991). This inherent resilience establishes *B. aegyptiaca* as a prioritized species for large-scale ecological restoration initiatives aimed at combating desertification, notably the Great Green Wall (GGW) Initiative.

Beyond its ecological role in semi-arid ecosystems, the species provides essential socio-economic services. All parts of the tree are exploited, offering food, fodder, medicine, and wood (Adamou et al., 2020; Abdou Habou et al., 2020; Sagna et al., 2014). The wood is particularly sought after for domestic energy (fuelwood/charcoal) and the manufacturing of agricultural tools due to its resistance and high calorific value (Abdou Habou et al., 2020; Adamou et al., 2020). Furthermore, its medicinal importance is significant, with the plant used to treat at least twenty-five diseases and symptoms (Abdou Habou et al., 2020; Abdou Habou et al., 2019), supported by the presence of bioactive compounds such as steroidal saponins, flavonoids, and alkaloids (Kamel et al., 1991; Speroni et al., 2005; Murthy et al., 2021; Chothani & Vaghasiya, 2011).

Despite its strategic importance, *B. aegyptiaca* stands face increasing vulnerability due to a combination of intense anthropogenic exploitation and the impacts of climate change (Abdou Habou et al., 2020; Massaoudou et al., 2022; Weber et al., 2018). The high demand for its products translates into substantial human pressure (Abdoulaye et al., 2017; Abdou Habou et al., 2020), which is compounded by low natural regeneration rates in many areas (Idrissa et al., 2018; Massaoudou et al., 2022). Local populations in Central-Eastern Niger perceive a general regression of the species, mainly attributing this decline to abusive cutting (38.46%) and drought (26.15%) (Abdou Habou et al., 2020; Abdou Habou et al., 2019). This unsustainable dynamic has led to the progressive scarcity of the species, notably observed in ecologically fragile areas like the Lake Chad Basin (Bio et al., 2021; Massaoudou et al., 2022), where stands exhibit a very low average density, confirming local rarefaction (Bio et al., 2021; Abdou Habou et al., 2020).

The demographic structure frequently observed in these vulnerable Sahelian populations, characterized by an inverted J-shaped distribution with a predominance of young individuals and a scarcity of large, mature subjects confirms active regeneration capacity but signals a strong pressure on adult cohorts. Understanding the specific ecological and human factors that drive this structural depletion is crucial for linking stand ecology with effective conservation strategies in dryland systems. While environmental variables like soil texture and land use are known to significantly influence the distribution and floristic composition of *B. aegyptiaca* stands in the Central-East Niger (Abdou Habou et al., 2020; Abdou Habou et al., 2019), the precise quantitative relationship between management intensity and structural attributes remains poorly defined.

This study aims to quantify the structural attributes and dynamics of *B. aegyptiaca* stands and utilize multivariate analysis to identify the key ecological and human factors driving their spatial organization in the Lake Chad Basin. We hypothesize (H_1) that the intensity of land-use patterns, rather than soil characteristics alone, is the principal determinant of structural variability, driving the observed rarity of adult cohorts. We further hypothesize (H_2) that intensified land use on productive soils results in strong selective pressure on mature individuals, leading to an unstable inverted J-shaped structure. By robustly testing the connection between ecological structure and management intensity, our work provides actionable scientific insights crucial for linking forest ecology with sustainable management strategies in vulnerable dryland systems worldwide.

2. Materials and Methods

2.1. Study Area

The present study was conducted in eastern Niger, specifically in the Gouré Department and the Diffa Region (Figure 1). The Gouré 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 Gouré receives approximately 420 mm. The average annual temperature is 27.9°C in Diffa and 27.4°C in Gouré, with maximum temperatures reaching 40.82°C in May and minimum temperatures dropping to 11.59°C in January in Diffa. In Gouré, 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).

2.2. Sampling and data collection

As part of the characterization of *B. aegyptiaca* populations, dendrometric surveys were conducted in the same plots used for phytosociological assessments. A stratified sampling design was established based on land use types, following the distribution below 120 plots of 2,500 m² each in agroforestry and agropastoral systems and 80 plots of 1,000 m² each in pastoral rangelands. This sampling layout (illustrated in Figure 2) ensured representative coverage of all major land use categories within the study area. In each plot, data were recorded for all *B. aegyptiaca* individuals, including individual density, Diameter at breast height (DBH), total height, mean canopy cover, and composition of associated plant species. These measurements were subsequently used to compute the main dendrometric parameters, namely Density (N), Basal area (G), and Mean cover (r).

2.3. Environmental and management variables

Nine environmental variables were recorded for each plot. These variables characterized the key ecological and human factors hypothesized to drive stand organization:

Land Use type: Agrosystem vs. Sylvo-pastoral system.

Geomorphology (depression, slope, dune, plain).

Soil texture: Determined through tactile testing (clayey, sandy-clay, sandy).

2.4. Data processing and multivariate analysis

Statistical analyses focused on linking the observed stand ecology (species composition, structural attributes) to the measured environmental and land-use variables.

2.4.1. Quantification of dendrometric parameters

In each plot, the measured parameters included the density of *B. aegyptiaca* individuals, the diameter at breast height (DBH), the total height, and the two perpendicular crown diameters. The main structural variables were then calculated using the following formulas:

Density (N): Density represents the number of individuals per unit area: $N = n/S$ where n: total number of individuals recorded; S: plot area (in hectares).

Basal area (g): The basal area corresponds to the sum of the cross-sectional areas (measured at 1.3 m above the ground) of all individuals with a diameter greater than 5 cm, expressed per unit area of the plot: $G = \pi/4 \sum d_i^2 / S$ Eq. (A.1), where: d_i = diameter of individual i (in cm), S = plot area (in m²).

Canopy cover (r): Canopy cover represents the ground surface effectively covered by the projection of the tree crown: $r = \pi \times (D_{\text{moyen}}/2)^2 / S$ Eq. (A.2), where D_{moyen} is the mean of the two perpendicular crown diameters.

2.4.2. Multivariate and non-parametric analyses of structural drivers and species co-occurrence

Statistical evaluation began by confirming that the data did not follow a normal distribution, thereby justifying the application of non-parametric tests. The Kruskal-Wallis test was subsequently used to assess differences in structural variables, including density, diameter at breast height (DBH), total height, and canopy cover, across various stands or Land-use types. To specifically analyze floristic associations, a presence-absence contingency table examined the co-occurrence of *B. aegyptiaca* and *Vachellia tortilis*. Fisher's exact test indicated a statistically significant association ($p = 0.011$, $\alpha = 0.05$), demonstrating that this co-occurrence was unlikely to be due to random chance. Further quantification using the Jaccard similarity index revealed a moderate to strong co-occurrence, with values reaching approximately 0.5 in some sites. To determine how environmental variables influenced the plant group distribution, Canonical Correspondence Analysis (CCA) was employed, which quantified the variance explained by the environmental gradient and identified variables exhibiting statistically significant effects (). Furthermore, to specifically examine structural variability and the selective pressure impacting adult cohorts, Mixed Data Factor Analysis (AFDM) was utilized. AFDM enabled the quantification and visualization of relationships between non-metric environmental variables (such as Land Use and Soil Texture) and the spatial distribution of individual *B. aegyptiaca* trees, offering a robust test of the principal determinants driving spatial organization and the rarity of adult cohorts. All statistical procedures were executed using R software (version 4.5.1) within RStudio (version 2025.09.1+401).

3. Results

3.1. General characteristics of the stands

Table 1 presents the mean values and standard deviations of the main dendrometric parameters of *B. aegyptiaca* in the study area. The average diameter at breast height (DBH) is 17.91 ± 10.73 cm, with a mean height of 4.79 ± 1.63 m, values that are consistent with those reported for the Lake Chad Basin (20.19 ± 10.6 cm and 4.95 ± 1.59 m, respectively). The average density is

estimated at 23.04 ± 20.92 stems ha^{-1} , reflecting a non-uniform distribution of individuals and a strong influence of edaphic and anthropogenic factors. In comparison, densities in the Lake Chad Basin are lower (4.02 ± 2.7 stems ha^{-1}), highlighting the scarcity of dense stands in that region. Finally, the mean basal area (0.01022 ± 0.00902 m^2) and canopy cover (12.68 ± 2.93 m^2) indicate a modest plant cover and scattered stands, characteristic of open Sahelian formations.

3.2. Analyses according to land use

Figure 1 shows that the average height of *B. aegyptiaca* individuals varies across different land-use types. Figure 3 illustrates differences in diameter at breast height (DBH), with cultivated fields and agropastoral parks which are less exploited tending to exhibit the largest DBH values.

Figure 4 highlights the strong variability in density (stems ha^{-1}), which is generally lower in rangelands subjected to grazing or wood harvesting, while fallow lands display higher densities. Figure 5 (listed as Figure 7 in the source) shows the variation in basal area (g) according to land use, directly reflecting the biomass and ecological structure of the stands. Finally, Figure 6 emphasizes significant differences in canopy cover, with an overall average of 12.68 m^2 .

3.3. Dynamics of the stands

The demographic structure of *B. aegyptiaca* is clearly illustrated in Figure 8 (overall diameter class distribution) and Figure 9 (stratification by land use). The distribution of individuals consistently exhibits an inverted “J” shape, indicating a predominance of young or small-diameter trees within the [10-50 cm) diameter class, which reflects active natural regeneration. However, an imbalance is evident due to the scarcity of large individuals (≥ 40 cm), suggesting that mature trees are under strong pressure, potentially from overexploitation or increased mortality. The floristic association between *B. aegyptiaca* and *Vachellia tortilis* is highlighted in Figures 10 and 11. Table 2 shows that, out of 15 analyzed surveys, there were no occurrences of *B. aegyptiaca* without *V. tortilis*, while 4 cases of co-occurrence were recorded. This dependency is strongly supported by statistical analyses: Fisher’s exact test confirmed a significant association ($p = 0.011$), and the Jaccard similarity heatmap (Figure 11) corroborates this affinity, with a similarity index of 0.5 at certain sites.

3.4. Influence of soil texture and land use on individual distribution

The FAMD graphs depict the distribution of individuals on the factorial plane defined by Dimension 1 (Dim1, 16.9% of inertia) and Dimension 2 (Dim2, 13%), together explaining approximately 30% of the total variability. Dim1 is the most structuring axis, mainly separating individuals along a horizontal gradient, whereas Dim2 reflects vertical dispersion, linked to environmental and anthropogenic factors. The distribution by soil texture (Figure 12) shows that individuals from Sandy-Clayey and Sandy soils cluster on the left of Dim1, corresponding to less exploited areas and rangelands. Individuals from Loamy-Sandy and Loamy soils project to the right, associated with cultivated lands and agro-parks, while Sandy-Loamy soils are vertically separated, reflecting more intensive management practices. These patterns indicate that soil texture is a major factor differentiating individuals, with Dim1 opposing little-exploited soils and cultivated loamy soils. Analysis by land-use type (Figure 13) confirms these trends:

unexploited rangelands occupy the left pole of Dim1, while cultivated lands and agro-parks appear on the right, reflecting increasing management intensity. Agro-parks occupy an intermediate position, highlighting that land use is a key determinant of the spatial organization of the stands. The variable contribution graph (Figure 14) shows that Dim1 is dominated by structural variables (canopy cover, height, mean diameter, basal area), representing a gradient of vegetation structure. In contrast, Dim2 is primarily influenced by management and environmental variables (land use, human impact, geomorphology), reflecting the intensity of human activities and large-scale environmental conditions.

4. Discussion

4.1. Ecological resilience and the global mandate for *B. aegyptiaca* management

The structural and phytoecological characteristics of *B. aegyptiaca* (*B. aegyptiaca*) stands in the Lake Chad Basin reaffirm the species' ecological importance and adaptability in arid environments. *B. aegyptiaca* is recognized globally as a vital multipurpose tree, prized for its wide ecological amplitude and strong resistance to drought across Sahelian and Sudano-Sahelian zones (Sagna et al., 2014; Tesfaye, 2015; Murthy et al., 2021; Arbonnier, 2000; Ousmane et al., 2023). This resilience justifies its prominent role in large-scale ecological programs, such as the Great Green Wall (GGW) Initiative (Sagna et al., 2014; Abdou Habou et al., 2021).

The species' massive utility encompassing food, fodder, wood, and traditional medicine translates its ecological success directly into socio-economic value (Adamou et al., 2020; Abdou Habou et al., 2020). For instance, its medicinal properties, including anti-inflammatory, anti-nociceptive, and antioxidant activities demonstrated *in vivo* (Speroni et al., 2005; Chothani & Vaghasiya, 2011; Murthy et al., 2021), and its use in treating at least twenty-five diseases and symptoms (Abdou Habou et al., 2020), underscore its critical function in local human and animal welfare (Ousmane et al., 2023).

4.2. Stand structure and dynamics

The study of the Lake Chad Basin reveals a low average density of *B. aegyptiaca* stands (4.02 ± 2.7 stems ha^{-1}), indicating a local scarcity. This density is significantly lower than those reported in other agroforestry parks in Niger, where the species is often dominant (occupancy rates up to 93%). For instance, in the Tillaberi region (southwestern Niger), densities ranging from 44.88 to 74.52 stems ha^{-1} have been reported (Adamou *et al.*, 2020). The dendrometric values reported in this study mean diameter at breast height (17.91 ± 10.73 cm) and mean height (4.79 ± 1.63 m) are, however, consistent with the dimensions of mature individuals observed in the Tillaberi parks. The observed demographic profile, characterized by a predominance of young individuals (inverted “J” curve) and a scarcity of large trees (diameter > 40 cm), is a common feature of populations under strong anthropogenic pressure. Active natural regeneration is confirmed, a phenomenon widely reported elsewhere in Niger, with high recruitment rates ranging from 76.71% to 90.54% (Adamou *et al.*, 2020). Regeneration occurs primarily through seed dispersal (81.2%), stump sprouting (13.5%), and suckering (5.2%) (Massaoudou *et al.*, 2022). Notably, ingestion of fruits by goats helps to break seed coat

dormancy, leading to high germination rates (up to 76.87%) (Abdou Habou *et al.*, 2019). Furthermore, seedling growth is cryptogeal, with the taproot developing more than the aerial part (78.59 ± 9.04 cm vs. 61.8 ± 6.2 cm after six months) (Abdou Habou *et al.*, 2019), an essential adaptation to drought and herbivory in the Sahelian zone. Nevertheless, the scarcity of adult trees in the study area suggests that these young individuals face excessively high post-recruitment mortality.

4.3. Ecological factors and floristic associations

The study highlights a significant association between *B. aegyptiaca* and *V. tortilis* ($p = 0.011$). This association is a well-documented phytoecological trait in southeastern Niger, where the *B. aegyptiaca*-*V. tortilis* community has been identified as one of the principal vegetation assemblages (Abdou Habou *et al.*, 2020). The Factor Analysis of Mixed Data (FAMD) in this study further confirmed that environmental variables, such as land-use type (silvopastoral systems and agroforestry systems) and soil texture, significantly influence the distribution of these plant communities. This finding is consistent with the recognized ecological role of the species in enhancing soil quality. Previous studies in Niger have shown that soils beneath the canopy of *B. aegyptiaca* contain higher levels of magnesium, sodium, potassium, assimilable phosphorus, and nitrogen compared to open soils (Idrissa *et al.*, 2019). This role as a “fertility hotspot” is attributed to nutrient recycling and rainwater leaching and deposition processes (Idrissa *et al.*, 2019).

5. Conclusion

This investigation characterized the structure and dynamics of *B. aegyptiaca* stands in the Lake Chad basin, confirming that while the population exhibits active natural regeneration indicated by the inverted 'J' demographic curve it suffers from a low overall mean density. Crucially, the extreme rarity of large, mature individuals signals a severe demographic bottleneck driven by high post-recruitment mortality. Utilizing Mixed Data Factor Analysis, we demonstrated that this structural variability and spatial organization are significantly determined by key non-metric factors, specifically Land Use and Soil Texture, revealing that intensive cultivation and management practices exert selective pressure opposing stands in less exploited areas. This advance in understanding the underlying structural determinants is critical because *B. aegyptiaca* holds immense ecological value crucial for combating desertification and enhancing soil stability and provides vital socioeconomic and medicinal resources. Consequently, the central implication for sustainable forest management is the urgent need to implement targeted conservation strategies focused on mitigating excessive anthropogenic pressures, such as abusive cutting, to effectively safeguard the remaining adult cohorts and ensure the long-term persistence and ecological function of this strategic multipurpose species across vulnerable Sahelian agrosystems.

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Author Contributions

B.Y.I. conceived and designed the study. B.Y.I., M.M.B., S.I. and M.A. participated in field surveys, data collection, and data validation. B.Y.I. performed the formal data analysis and prepared the original manuscript draft. B.Y.I., M.M.B., S.I. and M.A. contributed to data interpretation and manuscript development. M.M.B., S.I., and M.A. critically reviewed and revised the manuscript. All authors read and approved the final version of the manuscript.

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Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

Declarations

Ethics and consent to participate

The study involved field observations and sampling of wild populations of *Balanites aegyptiaca* (L.) Delile. The collection of plant material was conducted in accordance with applicable national and local guidelines for research on wild plant species in Niger. The authors confirm that the study complied with relevant regulations and that appropriate permissions were obtained where required.

The plant species was identified by Professor Mahamane Ali based on morphological characteristics and taxonomic references. Voucher specimens of *Balanites aegyptiaca* are preserved in the Herbarium Niger, Department of Biology, University of Niamey, Niger, under voucher number ES N° 879.

Plant materials were collected from natural populations of *Balanites aegyptiaca* in Sahelian drylands of Niger. Field activities were conducted with the authorization of relevant local authorities and in accordance with national guidelines governing the collection and study of wild plant resources. No endangered or protected plant species were collected during this study.

Clinical Trial Registration

Not applicable.

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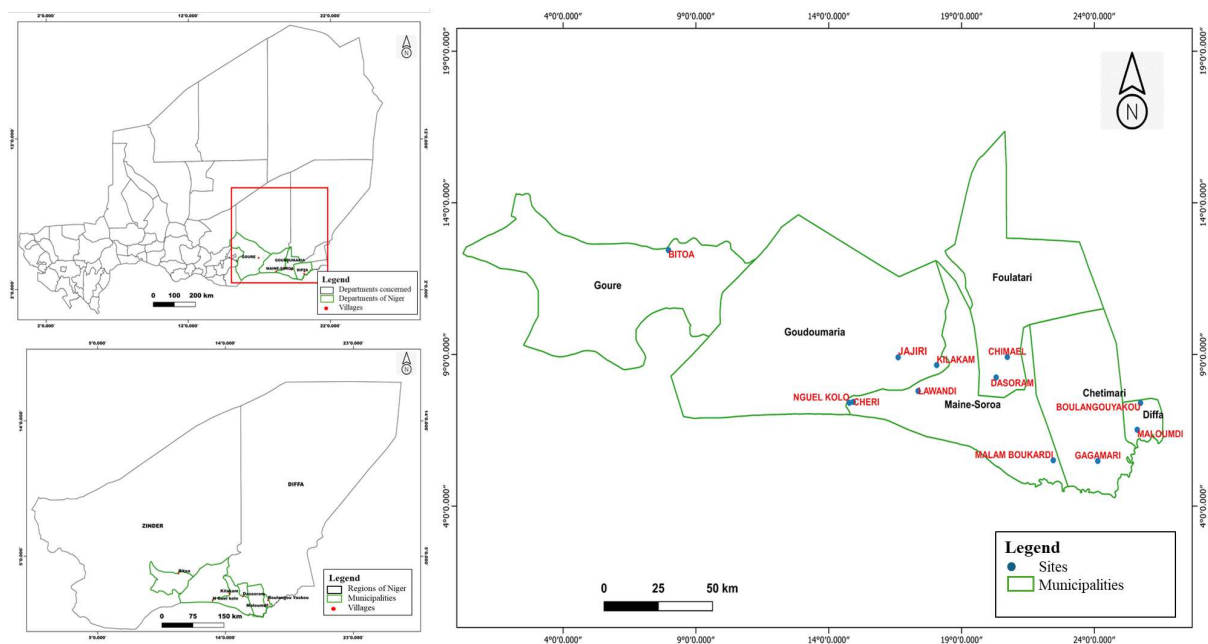


Figure 1. Study area

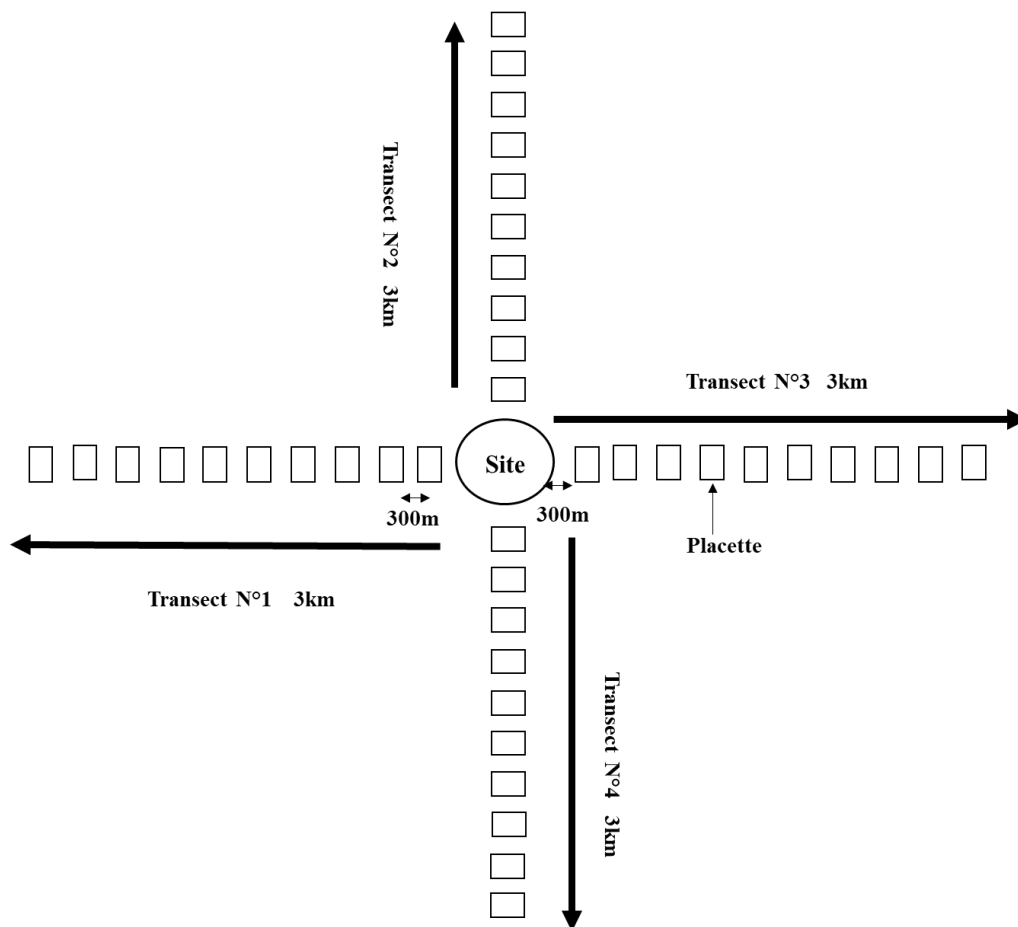


Figure 2. Plot-based floristic survey

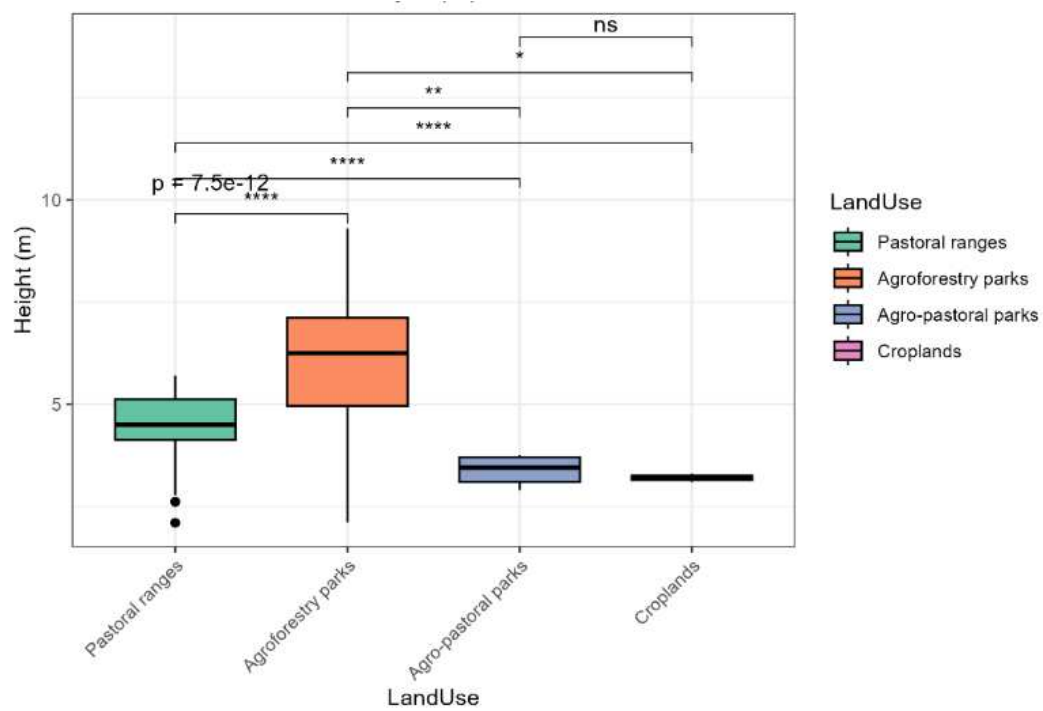


Figure 3. Height by Land-Use type

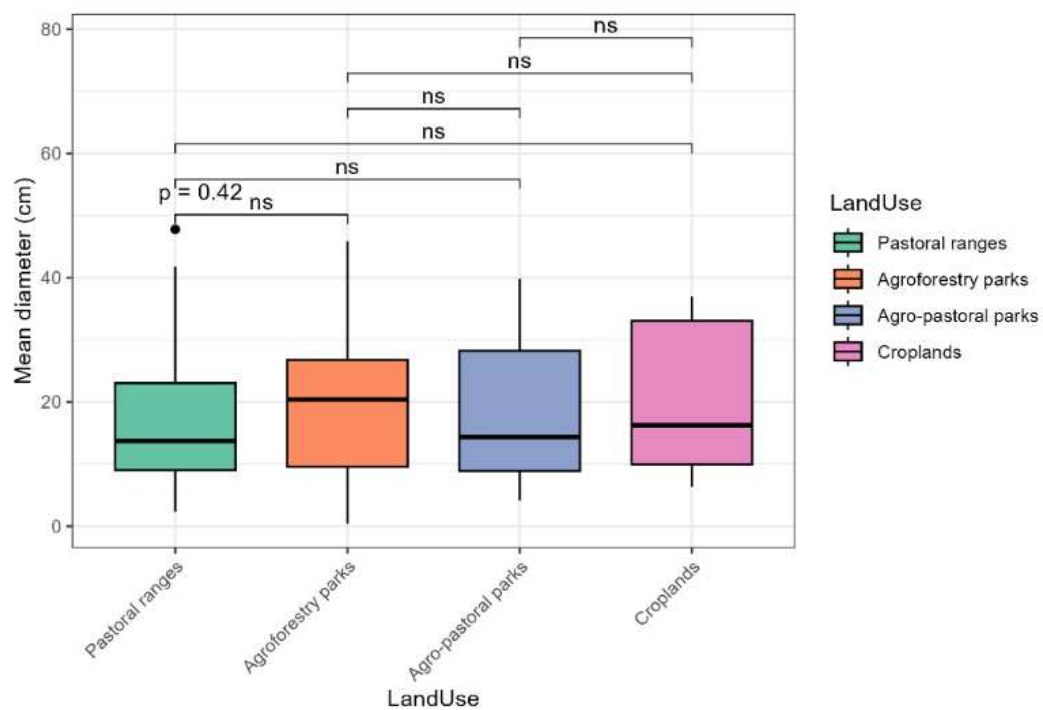


Figure 4. Diameter by Land-Use type

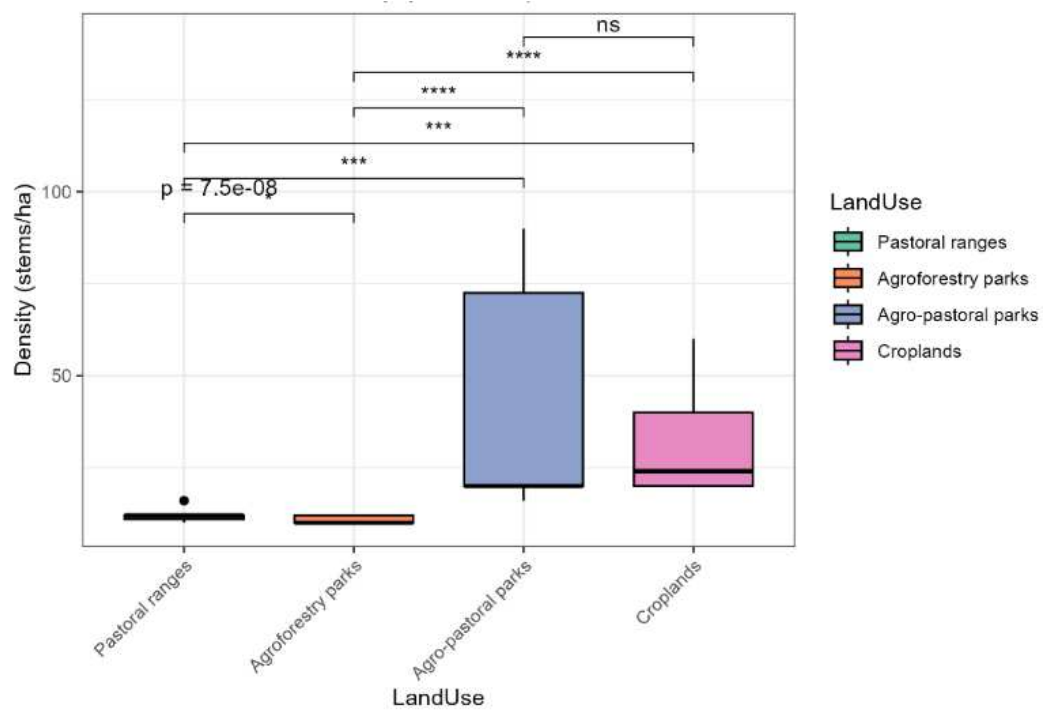


Figure 5. Density by Land-Use type

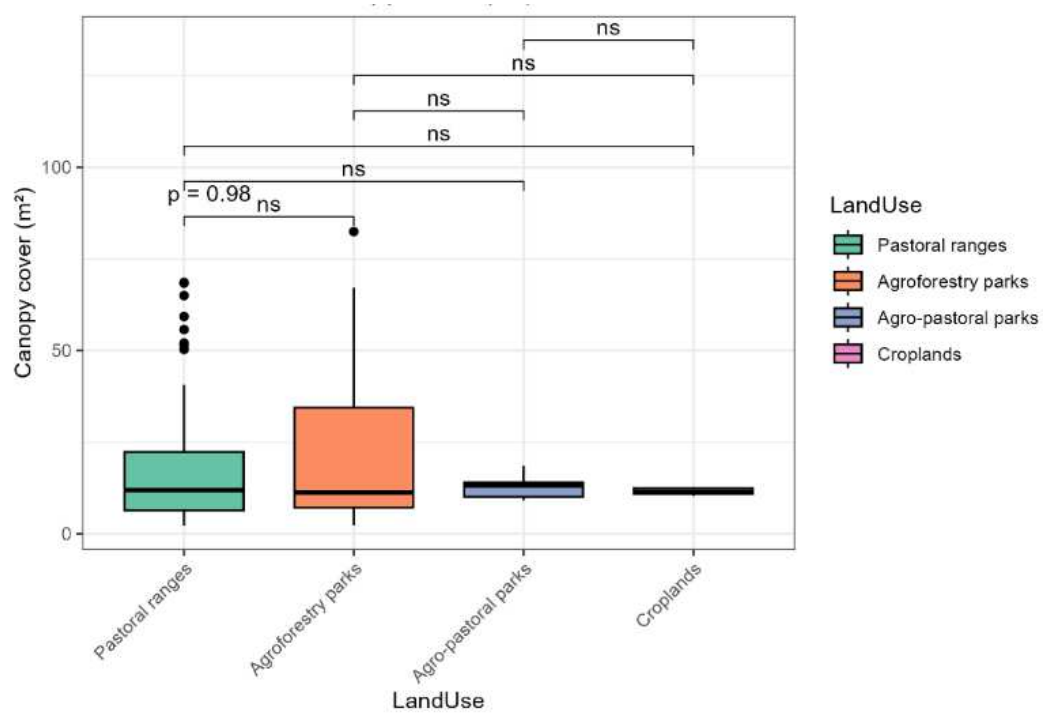


Figure 6. Canopy Cover by Land-Use type.

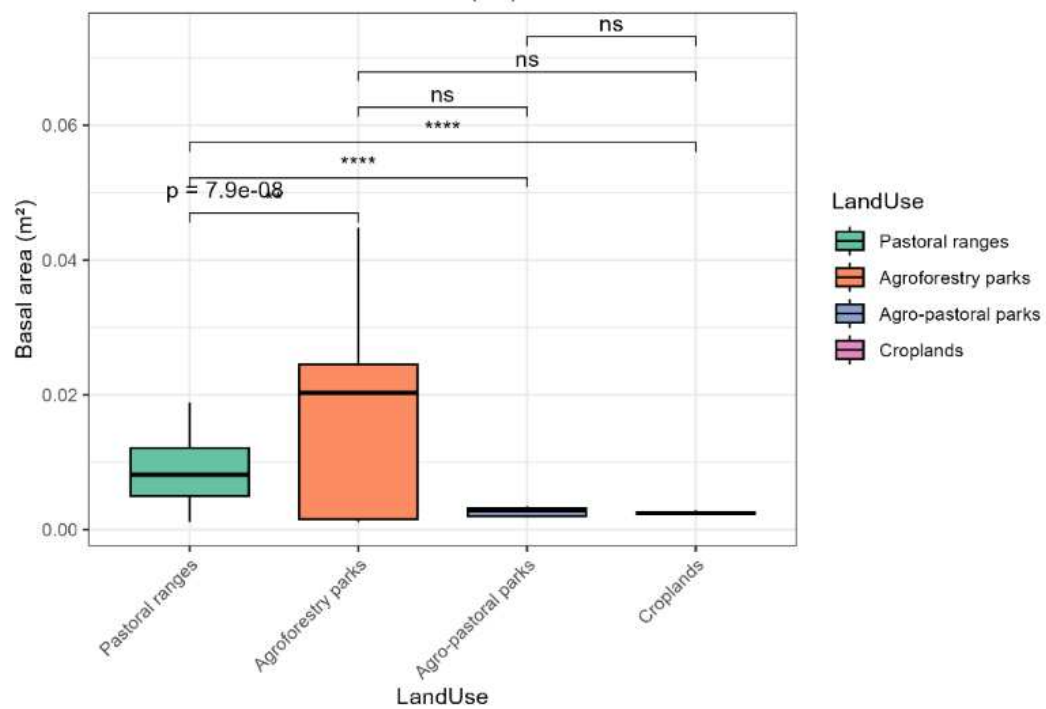


Figure 7. Basal area by Land-Use type.

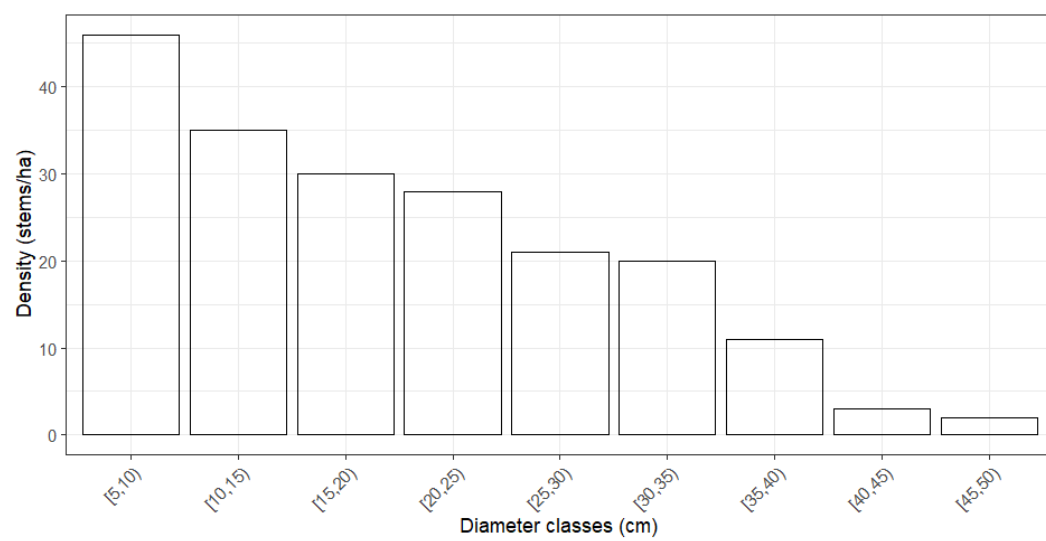


Figure 8. Global diameter class distribution of *B. aegyptiaca*.

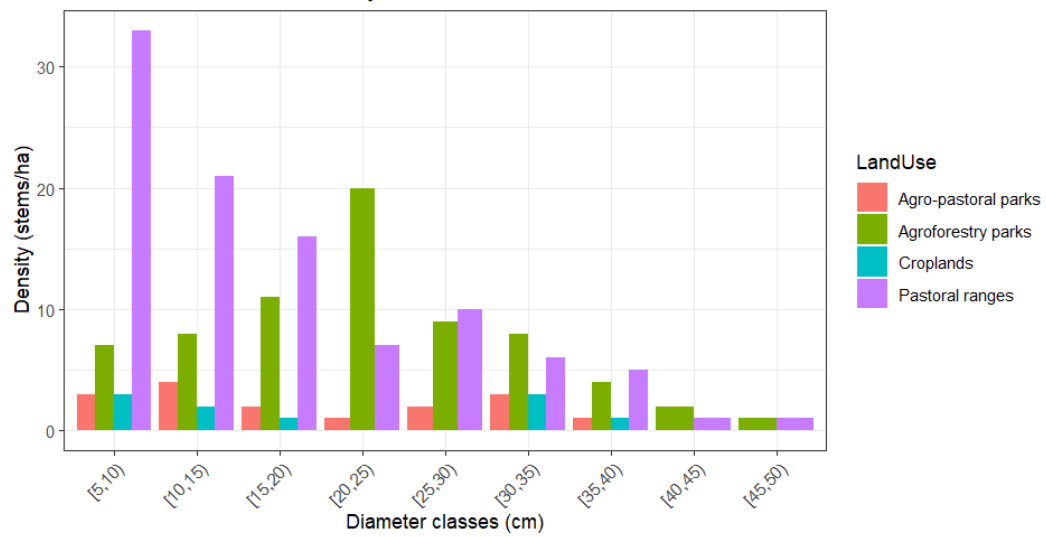


Figure 9. Diameter class distribution of *B. aegyptiaca* according to Land-Use type.

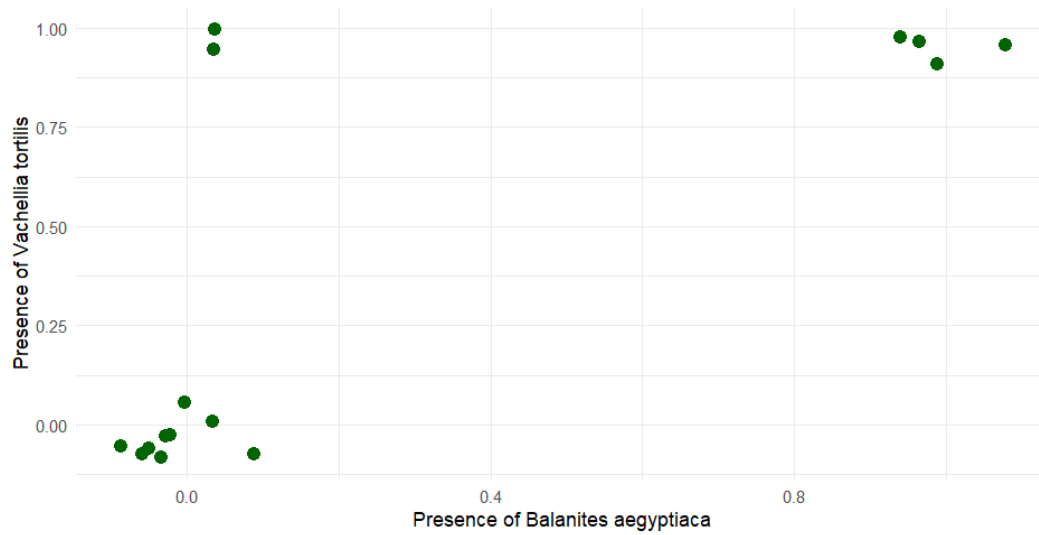


Figure 10. Floristic co-occurrence of *B. aegyptiaca* and *V. tortilis*

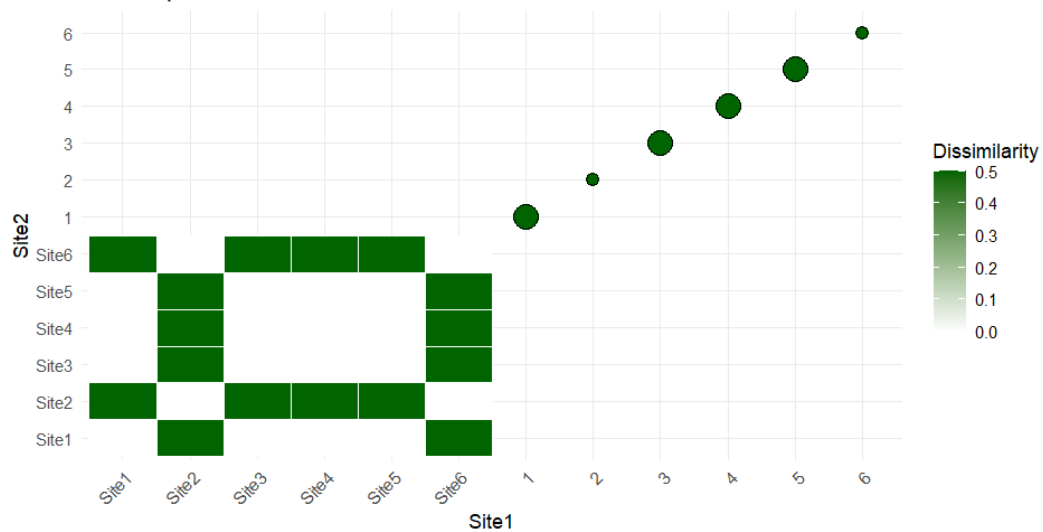


Figure 11. Heatmap of Jaccard dissimilarity highlighting co-occurrence between species.

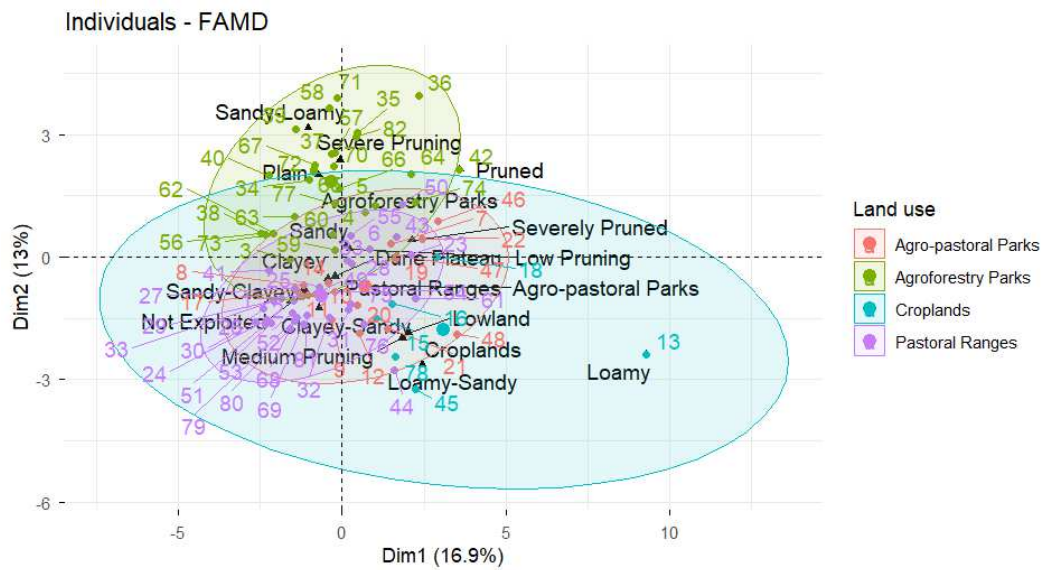


Figure 12. Distribution of individuals on the FAMD factorial plane (Dim1 $\times$ Dim2) according to Land-Use type.

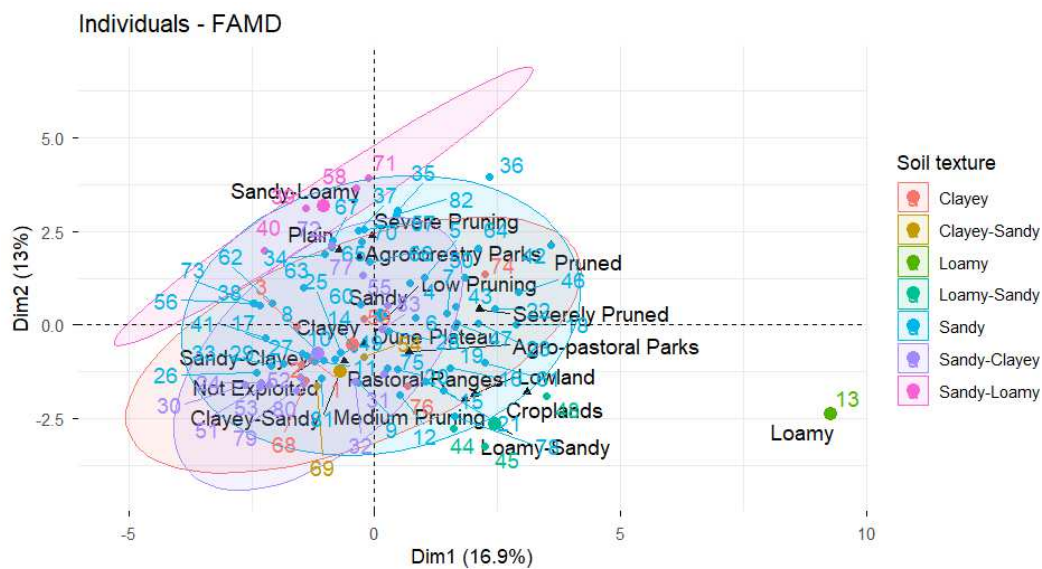


Figure 13. Distribution of individuals on the FAMD factorial plane (Dim1 $\times$ Dim2) according to soil texture.

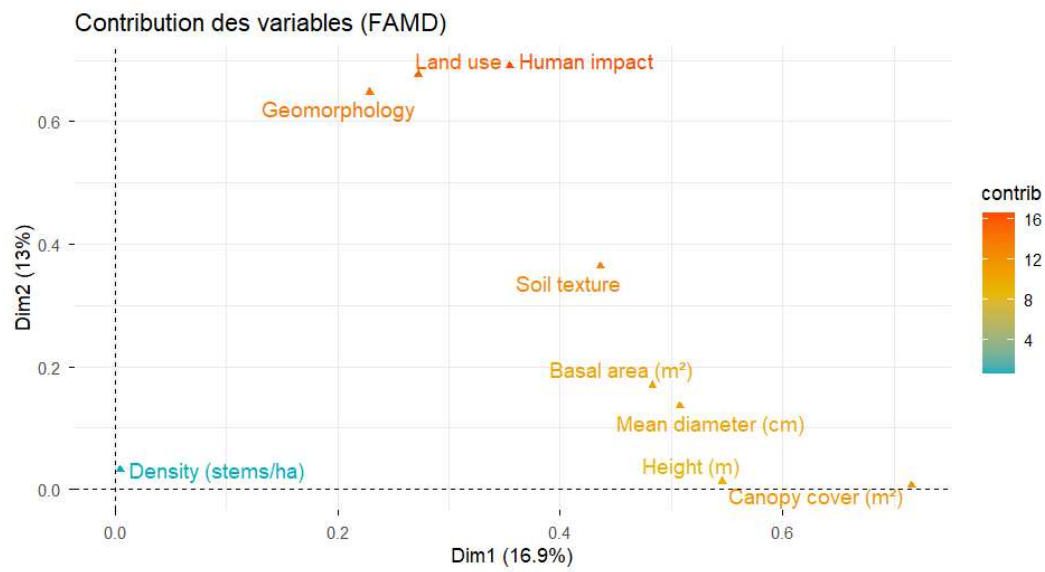


Figure 14. Contribution des variables aux deux premières dimensions factorielles (Dim1 et Dim2) de l'AFDM

Table 1. Dendrometric parameters measured on all individuals of *B. aegyptiaca*

Variables	Means	Standard deviations
Diameter (cm)	17.91	10.73
Height (m)	4.79	1.63
Density (stems/ha)	23.04	20.92
Basal area (m ²)	0.01022	0.00902
Cover (m ²)	12.68	2.93

Table 2. Floristic co-occurrence Between *B. aegyptiaca* and *Vachellia tortilis*

	<i>V. tortilis</i> = 0	<i>V. tortilis</i> = 1
<i>B. aegyptiaca</i> = 0	9	2
<i>B. aegyptiaca</i> = 1	0	4