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Effects of land use and climate on the diversity and population structure in natural stands of *Detarium microcarpum* Guill. & Perr. (Fabaceae) in Burkina Faso (West Africa)

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A B S T R A C T

Detarium microcarpum Guill. & Perr. is a multipurpose species, providing many ecosystem services. However, in its geographical range, its multiple uses represent a major challenge to the sustainable management and conservation of its resources. This study aimed to determine the effect of climatic zones, land uses, and their interaction on the natural stands of *D. microcarpum.* Inventories were conducted in 165 plots in two climatic zones and land use types in Burkina Faso. Hill diversity indices were used to determine the effects of climatic zones, land uses, and their interaction on *D. microcarpum* stand diversity. Generalized linear models were used to assess the effect of the abiotic and biotic factors on the species' structural parameters. Land uses and climatic zones significantly affected *D. microcarpum* stand diversity and structure. The lowest stand diversity was recorded in the unprotected areas. The similarity in woody species composition between land uses and climatic zones was low, indicating high beta diversity. The generalized linear model showed that rainfall, temperature, habitat heterospecific density, and habitat-specific richness significantly influenced the structural parameters of the *D. microcarpum* population. The diameter classes' distribution revealed unstable populations for the adult stratum, independent of climatic zones and land use types, except for the protected area in the Sudanian zone. The height class distribution of the juvenile stratum highlighted the instability regeneration of *D. microcarpum* populations. This study highlighted the instability of *D. microcarpum* populations and the specific effects of biotic and abiotic variables on the species' structural parameters. Thus, the findings suggest urgent conservation measures to ensure sustainable utilisation and management of the species.

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1. Introduction

In the recent decade, several studies have focused on the conservation of multipurpose species due to the anthropogenic activities and climate threats (Kafoutchoni et al., 2018). These species have faced serious threats with the increasing agricultural intensification and the supply of non-timber forest products (NTFP) (Mensah et al., 2014; Gogoi, 2018). In addition, climate-induced land use change could indirectly drive species distribution via changes in forest stand composition and structure (Bohn et al., 2018). Climate change affects individual species and the way they interact with other organisms and their habitats, which alters the structure and function of ecosystems and the goods and services that natural systems provide to society (Diaz et al., 2019; Trisurat et al., 2023). In developing countries like Burkina Faso, the expansion of agriculture has additional impacts on the species composition and population dynamics (Kumar et al., 2023). Environmental deterioration, changes in habitat, inappropriate vegetation management, fragmentation, and deforestation modify biotic and abiotic conditions which affect the species dynamics (Zida et al., 2007; Bedair et al., 2021).

The human population growth has increased agricultural intensification and the demand for forest products (Maryo and Wendawek, 2014) which affects biodiversity through the loss of species (Lompo et al., 2021). Deforestation leads to biodiversity loss and forest degradation, which contributes to global climate change (Coulibaly et al., 2021). The overexploitation of multipurpose species related to the strong demographic growth in Sub-Saharan African countries impairs the survival of many woody species (Zerbo et al., 2023) and impacts the ecological functions of savanna ecosystems (Balima et al., 2020).

However, at smaller scales, microclimatic conditions and species' competitive abilities influence the species structure and their composition (Mensah et al., 2018; Atanasso et al., 2019). Understanding the direction and magnitude of ecological responses allows forest manager to better anticipate these changes and their adaptation (Sirakaya, 2022). With human population pressure and climate change, it is expected that more natural landscapes will be converted into farmlands to further worsen the current state of biodiversity (Shiferaw et al., 2004). The intensive use of land for agriculture and the high demand for the species of wood for different purposes combined with the climate threat is leading to the loss of multipurpose species (Maryo and Wendawek, 2014).

Burkina Faso, like other tropical countries, has a remarkable biodiversity of endemic plants which are threatened by several factors including climate and human disturbances (Sintayehu, 2018). In addition, several overexploited woody species with deficient regeneration were declining in savanna due to the lack of conservation and insufficiency of data on their status which could help to propose appropriate management solutions (Bationo, Ouedraogo, et al., 2001). Indeed, among the woody species producing non-timber forest products, *Detarium microcarpum* is one of the most exploited and vulnerable species in Burkina Faso (Traoré et al. 2011; Gaisberger et al., 2017; Traore et al., 2020). Despite the widely recognized importance of *D. microcarpum* for the human uses (Bationo et al., 2001; Dimobe et al., 2018), little information is available for the effect of climate and land use on its populations' status.

Previous studies on *D. microcarpum* focused on its regeneration pattern and population structure in Burkina Faso (Bationo et al., 2001; Bastide and Ouedraogo, 2008; Maré and Millogo, 2019) and in Cameroon (Lamy et al., 2021). In addition others studies have been conducted on the local uses and the conservatiuon of the species in Benin (Sinadouwirou et al., 2022; Houénon et al., 2022) and in Mali (Kouyaté et al., 2002; Kouyaté, 2005) and the fruits nutritional values in Burkina Faso (Cavin, 2007). Among all these studies, none focused implicitly on the impact of climate, land use, and their interaction in their natural stand diversity, their population dendrometric characteristics and structure. It has been acknowledged that climate conditions influence woody species population (Traore et al., 2022; Zerbo et al., 2023), and the dynamic of a stand is influenced more by the type of land use (Balima et al., 2020; Zerbo et al., 2023). In addition, others authors pointed that dendrometric parameters are valid indicators of information on the conservation status of the species (Nichols et al., 2008; Deluaux and Van Damme, 2021). Given the increasing pressures on the savannah multipurpose species such as *D. microcarpum* and the lack of data for their sustainable management, it is urgent to assess how climate and human land use interact to affect its conservation. When population densities increase, the completion for space and resources is impacted (Janovský et al., 2013) and affects the species' survival (Atanasso et al., 2019). In addition, the individuals that first occupy a given area may monopolize the most suitable habitats which affects the structural parameters of the other species. In this context, it is crucial to understand how abiotic factors (temperature and precipitation) and biotic drivers (Habitat heterospecific tree density, habitat-specific richness) influence the structure and composition of tree species in their natural stand. This study expected that climatic variables (mean temperature, sum of precipitation) and biotic factors (Global density of the species, species richness) influence the dendrometric parameters of *D. microcarpum* on their natural stand. Knowledge of the species reaction to the climate effect is an important information for their conservation planning (Adjonou et al., 2020). Additionally, understanding the relationships between the species, stand structure, human disturbance and climate effect is essential for its sustainable management. This study aims to determine the effect of climatic zones, land uses, and their interaction on the natural stand's diversity and the population structure of *D. microcarpum*. Specifically, it:

i. Assess the influence of land uses and climatic zones on the diversity and the composition of woody species associated with *D. microcarpum* stands;
ii. determine how the *D. microcarpum* population responds to abiotic factors (temperature, precipitation) and biotic factors (habitat heterospecific density and habitat-specific richness) through its structural parameters.
iii. analyze the population structure of *D. microcarpum* across the land use types and the climatic zones.

2. Material and methods

2.1. Study sites

The study was carried out in the Sudanian and the Sudano-Sahelian climatic zones of Burkina Faso, which represent the natural occurrence areas of *D. microcarpum* in the country (Fig. 1). It was done from September to December 2022. Along to the climatic gradient, four study sites in protected and unprotected areas were chosen based on the presence of the *Detarium microcarpum*, and their accessibility due to the security issue that the country is facing. In each climatic zone, the distance between sites was more than 60 km. Besides, in each climate zone, the distance between sites representing protected and unprotected areas was 500 m.

In the Soudanian zone, the Protected areas were the Wildlife Reserve of Bontioli (South-Western) and the Classified Forest of Kou. The main ethnic groups encountered around the Classified Forest of Kou are Bobo, while the ones found around the Wildlife Reserve of Bontioli are Dagara. In the Sudano-Sahelian zone, the Protected areas consisted of the Game Ranch of Nazinga and the Classified Forest of Nakambe. The main ethnic groups of the two sites are Mossi for the Classified Forest of Nakambe and Gourounsi for the Game Ranch of Nazinga.

The vegetation in the four Protected areas is characterized by various savanna types including shrub savannas, tree savannas, woodlands, dry forests, and gallery forests (Nacoulma et al., 2018). The Protected areas such as the Classified Forest of Kou, the Wildlife Reserve of Bontioli, and the Classified Forest of Nakambe were found along the rivers of Kou, Bougouriba, and Nakambe. The Unprotected areas were dominated by agroforestry parks.

The mean annual rainfall increases from the Sudano-Sahelian zone to the Sudanian zone in contrast to the mean annual temperature which decreases. According to the climate data from the National Meteorological Office, the annual rainfall ranges between 900 and 1100 mm in the Sudanian zone and between 600 and 900 mm in the Sudano-Sahelian zone. The mean annual temperature in the Sudanian zone was 27.5 °C and the found in the Sudano-Sahelian zone was 28.9 °C. In the Sudanian zone, the main activities of the population in the unprotected areas were the traditional mining exploitation around the Wildlife Reserve of Bontioli and the

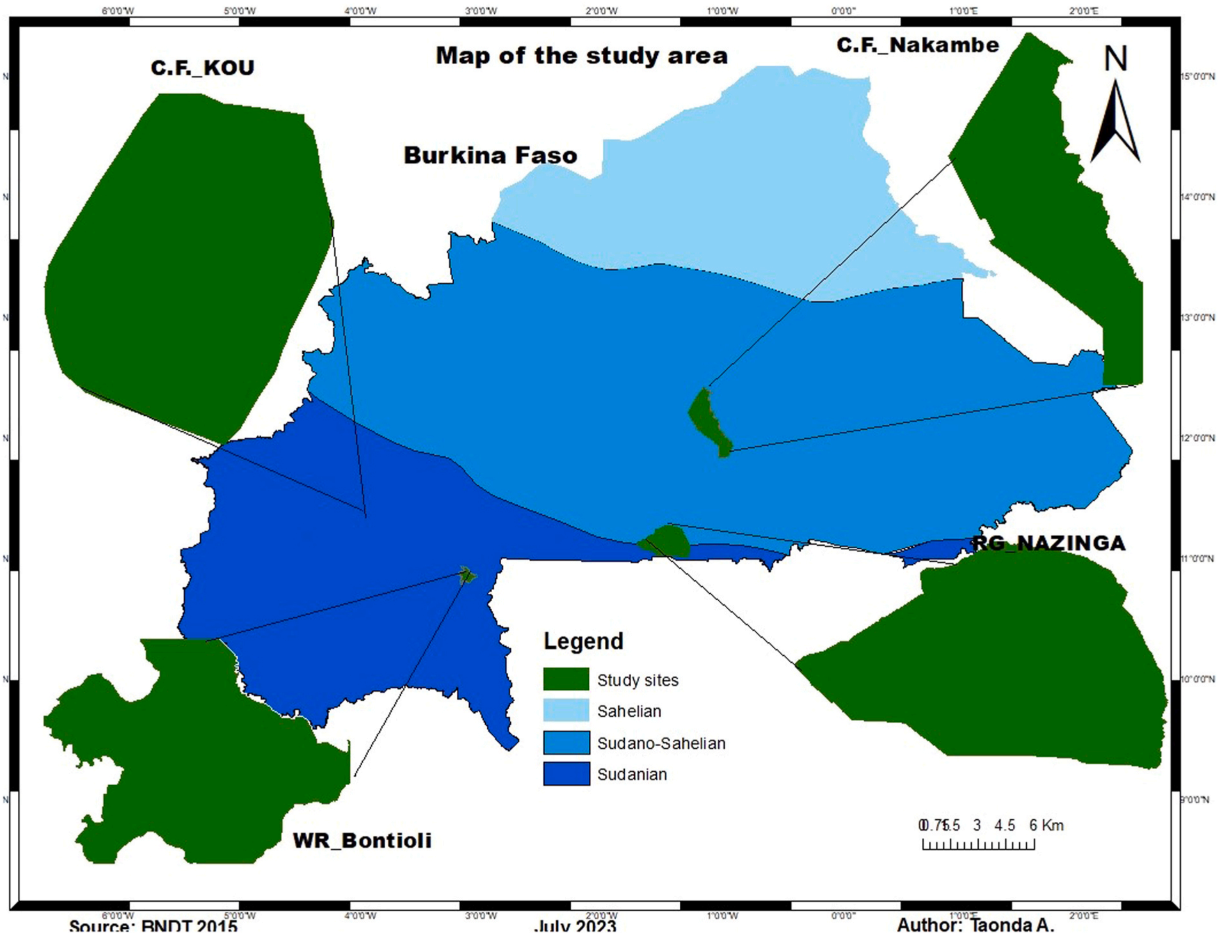

Fig. 1. Map of studied sites according to land occupation database of Burkina Faso in 2012.Legend: FC kou: Kou classified Forest; FC Nakambe: Nakambe Classified Forest; WR - Bontioli: wildlife reserve of Bontioli; RG Nazinga: Game Ranch of Nazinga

agriculture around the Classified Forest of Kou. In the Sudano-Sahelian zone, the main activities of the population living the surrounding the Game Ranch of Nazinga were agriculture, while around the Classified Forest of Nakambe, the main population activities were agriculture, wood exploitation and trading.

2.2. Study species

Detarium microcarpum is a woody species belonging to the Fabaceae family (Arbonnier, 2009)**.** It is a medium-sized tree and can reach up to 12 m high with a fairly dense spherical crown (Kouyaté, 2005; Maré and Millogo, 2019). The leaves of the species are composed of paripinnate with 5–6 pairs of opposite leaflets arranged alternately (Aubréville and Trochain, 1937). The flyers are 4–6 cm long and 3–4 cm wide, oval to elliptical, rounded at the ends, and emarginated at the top. The fruit is an ovoid or rounded pod, similar to a drupe, indehiscent with 2.5–4.5 cm in diameter (Aubréville and Trochain, 1937). The seed dispersers are often by animals (Bationo et al., 2001; Kamou et al., 2017). The species is found in dry savannas, dry forests, and fallow lands on sandy or iron-rich hard soils as well as scattered trees on farms (Kouyate et al., 2006; Houénon et al., 2021).

2.3. Sampling design and data collection

The study was conducted in two climatic zones (Sudano and Sudano-Sahelian). These climate zones were selected based on the presence of *Detarium microcarpum* natural stands. In each climate zone, data were collected in two protected areas and their surrounding areas (Unprotected areas) following an oriented sampling based on the presence of *D. microcarpum*. A total of 165 plots were set up in the two climatic zones. In the Sudanian zone, 75 plots comprising 45 plots in the Protected areas and 30 plots in the unprotected areas were used. In the Sudano-Sahelian zone, 90 plots including 50 plots for Protected areas and 40 plots in Unprotected areas were established. The plots in the protected areas had a size of 1000 m^2 (50 m x 20 m) and those in unprotected areas had a size of 2500 m^2 (50 m x 50 m) (Thiombiano et al., 2016; Balima et al., 2020). The plot sizes were followed the standard guidelines established by Thiombiano et al. (2016) for West Africa vegetation surveys. Within each site, the minimum distance between two plots was 100 m (Ouédroogo et al., 2020). In each plot, all woody species encountered were recorded for the assessment of *D. microcarpum* stand diversity and species composition. Forest inventories consisted of the measurements of the diameter at breast height (DBH) and the total height of each woody individual.

To characterize the regeneration of *D. microcarpum*, five sub-plots of 25 m^2 (5 m x 5 m) were installed in each major plot to sample juvenile individuals (DBH< 5 cm). In each sub-plot, the height of juvenile individuals of the species was measured using a diameter tape.

2.4. Data analyses

2.4.1. Variation in the stand's diversity and composition

All analyses were done with R statistical software (R Core Team, 2023). The taxonomic richness (number of species, genera, and families) of woody species associated with *D. microcarpum* was determined by investigating their co-occurrence in its natural stands (Zerbo et al., 2016). The recorded species names were further retrieved following the World Plant Names Index (https://wfoplantlist.org/plant-list/) and the Catalogue of vascular plants of Burkina Faso (Thiombiano et al., 2012).

The woody stand diversity was assessed through the series of diversity numbers and evenness presented by Hill (1973). The diversity indices were computed through the package Biodiversity R (Kindt, 2011) and were represented as follows:

- No = S; with *S* the number of species in a plot
- N1= $e^{H'}$; with H' Shannon's index;
- N2 = 1/D, *D* = is the Simpson's index
- Evenness (E) = $H/\ln(S)$.

A Multi-Way Analysis of Variance (Multi-Way ANOVA) was used to assess the effect of climate, land use, and their interaction on the diversity indices described by N0, N1, N2, and the Evenness. The Tukey's post-hoc test (Tukey-PHT) was used to compare the mean values according to the climatic zone and land-use types when needed.

To quantify the similarity among the species' natural stand, Jaccard similarity index (β-diversity) based on species data presence/absence was used to evaluate the variation in woody species composition according to the climatic zones and land use types.

The Importance Value Index (IVI) which is an indicator of species' ecological importance (Mueller-Dombois and Ellenberg, 1974) was used to determine the pattern of variation in *D. microcarpum* stands composition. This index ranges between 0 and 300. The species having the highest IVI is considered dominant in the community. The IVI was calculated for each heterospecific woody species according to the following parameters:

- Frequency = number of plots in which the species occurs/total plot number × 100.
- Relative Frequency = frequency of a species/sum of all frequencies × 100.
- Relative density = (number of individuals of a species / total number of individuals) × 100.
- Relative Dominance = total basal area of a species/basal area of all species × 100.
- Importance Value Index = Relative density + Relative dominance + Relative frequency

Table 1
Diversity indices of *Detarium microcarpum* stands (Mean ± standard deviation).

Parameters		Sudanian		Sudano-Sahelian		Anova multi-ways					
		protected areas	unprotected areas	protected areas	unprotected areas	F1	P1	F2	P2	F3	P3
N0 (Richness)	mean	19.55 ± 5.82a	12.43 ± 3.94b	14.7 ± 3.93b	11.62 ± 3.41b	20.74	0.0001***	48.98	0.0001***	8.31	0.0044**
	Overall	103	80	76	61						
N1 (Exp.^{H}).	mean	8.67 ± 3.96a	6.33 ± 2.57b	6.29 ± 2.14b	5.28 ± 1.55b	17.27	0.0001***	14.67	0.0001***	2.71	0. 1016 ^{ns}
	Overall	19.08	14.74	11.5	9.28						
N2 (1/D)	mean	4.83 ± 2.7a	3.97 ± 1.91ab	3.74 ± 1.39b	3.27 ± 1.03b	10.08	0.0017**	4.79	0.0299*	0.45	0.5030 ^{ns}
	Overall	5.35	4.45	3.91	3.4						
Evenness (E)	mean	0.80 ± 0.10a	0. 78 ± 0. 11a	0.74 ± 0.09a	0.72 ± 0.08a	4. 42	0.0371*	0.14	0.7069 ^{ns}	0.00	0.9618 ^{ns}
	Overall	0.636	0.614	0.564	0.542						

Legend: a, b = Tukey-HPT: Levels with different letters are significantly different; P= P value (line 358); P1 = P value of the difference climate zone, P2 = P value of the difference type of land use, P3 = P value of the interaction between climate zone and land use, *** P < 0.001, ** P < 0.01, * P < 0.05; ns = non-significant; F = F statistic of Fisher. F1= F statistic of the Sudanian zone; F2 = F statistic of the Sudano-Sahelian zone and F3 = F statistic of the interaction between the two climatic zones.

In each climatic zone and land use type, the 20 species with the highest IVI were selected to highlight the variation patterns in dominant woody species.

2.4.2. Variation of D. microcarpum structural parameters and effect of abiotic and biotic factors

The structural parameters of *D. microcarpum* included basal area (G), density (N), mean diameter (Dm), and Lorey's mean height (HL).

The basal area G was calculated as the following formula:

- G ($m^2.ha^{-1}$) = (π *DBH^2) /4).
- N (individuals/ha) = n/S, with n as the average number of individuals per plot and S as the area expressed in hectares.
- The average Lorey's height m ($\frac{\sum_{i=1}^{k} gihi}{\sum_{i=1}^{k} gi}$ with $gi = \frac{\pi}{4}di^2$) expresses the height of the individuals adjusted by the basal area.

The variation in the species' structural parameters according to the climatic zones and land use types were analysed through the non-parametric Kruskal Wallis test due to the non-normal distribution of data.

To determine the effects of abiotic (mean annual temperature and mean annual precipitation) and biotic factors ("habitats specific richness" and "heterospecific density") on the structural parameters of *D. microcarpum*, a generalized linear model assuming a Poisson distribution was applied. The "habitat heterospecific density" refers to the number of all individuals of the different species that occur within the same habitat with *Detarium microcarpum* stand. The "habitat-specific richness" refers to the number of the different species found within the same habitat with *Detarium microcarpum* species. Based on geographical coordinates, abiotic factors including climate data such as mean annual temperature (°C) and mean annual precipitation (mm) were downloaded for each plot from WorldClim (https://www.worldclim.org/data/worldclim21.html) through the R packages raster (Etten et al., 2023), SP (Hijmans et al., 2023), rgdal (Daniel and Anderson, 2018), exactextractr (Daniel, 2020), sf (Cook and Baston, 2023), terra (Hijmans, 2023) with a spatial resolution of 0.5.

Thus, abiotic (mean annual temperature and mean annual precipitation) and biotic (habitat heterospecific density and habitat specific richness) factors were used as explanatory variables and *D. microcarpum* structural parameters (basal area, density, mean diameter and Lorey's mean height) as response variables. In addition, the Pearson correlation was used to check the relationship between biotic factors (habitat-specific richness and heterospecific density) and abiotic factors (average temperature and mean annual precipitation) considered in the model as explanatory variables (Appendix 2).

2.4.3. Variation of D. microcarpum population structure

Diameter classes and height class distribution based on the method of Condit et al. (1998) were used to interpret the status of *D. microcarpum* populations according to the climatic zones and land use types. Thus, ten (10) diameter classes 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm, 25–30 cm, 30–35 cm, 35–40 cm, 40–45 cm, 45–50 cm and 50–55 cm for the adult stratum and five height classes 0–0.5 m, 0.5–1 m, 1–1.5 m, 1.5–2 m, 2–2.5 m for juvenile stratum were used. The resulting parameters, especially slope, R^2 coefficient of determination, and regression probability were considered as indicators of distribution status (Obiri et al., 2002). A negative slope indicates that small-diameter individuals are abundant, while a positive slope indicates an abundance of large-diameter individuals. In addition, values of the coefficient of determination (R^2) and their p-values make it possible to observe whether there is a stable transition between several individuals and diameter classes.

3. Results

3.1. Diversity and composition of Detarium microcarpum stands according to the climatic zones and land use types

3.1.1. Variation in D. microcarpum stands diversity according to the climatic zones and land use types

A total of 102 woody species belonging to 79 genera and 28 families were found at the four study sites (Appendix A). The most represented families were Fabaceae (30.37%), Anacardiaceae (6.32%), Combretaceae (6.32%), Malvaceae (6.32%), Apocynaceae (5.06%) and Phyllanthaceae (5.06%).

The analysis of the stand diversity by Hill numbers allowed underlining the variations of mean species numbers (N0), abundant species numbers (N1), and very abundant species numbers (N2) between climatic zones and land use types (Table 1). Species numbers, abundant species numbers, and very abundant species numbers decreased from the Sudanian zone to the Sudano-Sahelian zone.

Mean species numbers by plot (N0) showed that the Sudanian zone was significantly ($F = 20.74$, $p < 0.0001$) more diverse than the Sudano-Sahelian zone (Table 1). By considering the land use types, there was only a significant difference (F2=44.584, P2=< 0.0001) between the mean species numbers by plot (N0) found in the Protected areas (19.55 ± 5.82 species/plot) and the unprotected areas (12.43 ± 3.94 species/plot) of the Sudanian zone. However, no difference was observed between the mean species numbers by plot (N0) found in the different land uses of the Sudano-Sahelian zone. In addition, the interaction between the climatic zone and the land use type influenced significantly (8.31, P3=0.0044) the mean number of species per plot.

The analysis of the vegetation by N1 revealed that the climatic zone ($F1 = 17.27$, $P1 < 0.0001$) and the land use types (F2=14.561, P2=0.0001), significantly affected the number of abundant species. Besides, in the Sudanian zone, the number of abundant species varied from 8.67 ± 3.96 species in the protected areas to 6.33± 2.57 in the unprotected areas but did not differ between land protected and unprotected areas in the Sudano-Sahelian zone.

By considering $1/D$ ($N2$), the number of very abundant species decreased significantly from the Sudanian to the Sudano-Sahelian zone ($F1 = 10.08$, $P1 = 0.0017$). The type of land use also influenced significantly the number of very abundant species ($F2 = 5.1788$, $P2 = 0.02417$). In the Sudanian zone, the number of very abundant species was 4.83 ± 2.7 in the Protected areas and 3.97 ± 1.91 in the Unprotected areas. It varied from 3.74 ± 1.39 in the Protected to 3.27 ± 1.03 in the Unprotected areas in the Sudano-Sahelian climatic zone.

The Evenness pattern decreased significantly ($F1 = 4.42$, $P1 = 0.0371$) from the Sudanian to the Sudano-Sahelian zone. However, the type of land use ($F2 = 0.11$, $P = 0.7069$) and the interaction ($F3 = 0.00$ and $P3 = 0.9618$) between the climatic zone and the land use type did not influence the Evenness index. The value of the Evenness index ranges from 0.80 ± 0.10 in the Protected areas of the Sudanian zone to 0.72 ± 0.08 in the Unprotected areas of the Sudano-Sahelian zone.

3.1.2. Variation in D. microcarpum stands composition according to climatic zones and land use types

Jaccard's similarity index revealed a low similarity (< 50%) between the different habitats of *Detarium microcarpum* across the two climatic zones and land use types (Table 2). The highest similarity (0.49) were observed between the Sudanian Protected areas and Sudanian Unprotected areas. The lowest similarity (0.28) has been observed between the Sudanian Protected areas with the Sudano-Sahelian Unprotected areas.

The most dominant species associated with *D. microcarpum* varied according to climatic zones and land use types. In the protected areas of the Sudanian climatic zone, the most dominant species were *Combretum glutinosum*, *Vitellaria paradoxa*; *Burkea africana*, *Pterocarpus erinaceus*, *Hexalobus monopetalus*; *Entada Africana*; while in the unprotected areas of the same climatic zone, there were

Table 2
The first 20 dominant woody species encountered at the four sites along the climatic zones and land uses types based on importance value index (IVI).

Species	Sudanian climatic zone		Sudano-Sahelian climatic zone	
	protected areas	unprotected areas	protected areas	unprotected areas
Afzelia africana	-	4.73	2.26	-
Annona senegalensis	-	4.07	-	-
Balanites aegyptiaca	-	-	-	29.78
Bridelia ferruginea	-	-	-	4.64
Burkea africana	12.12	7.27	3.44	-
Cassia sieberiana	-	4.73	-	-
Combretum adenogonium	-	-	4.06	-
Combretum collinum	-	-	6.49	16.99
Combretum glutinosum	13.11	13.26	4.37	4.52
Combretum nigricans	4.46	-	-	-
Combretum paniculatum	-	-	2.50	-
Crosopteryx febrifuge	7.63	8.30	25.69	-
Daniella oliveri	-	5.02	-	-
Detarium microcarpum	68.60	58.14	113.19	99.77
Detarium senegalense	6.37	-	-	-
Diospyros mespiliformis	-	5.00	-	-
Entada africana	8.81	10.67	-	-
Gardenia erubescens	-	8.73	-	3.91
Gymnosporia senegalensis	-	-	5.27	-
Hexalobus monopetalus	8.83	6.28	-	-
Isoberlinia doka	4.66	-	7.42	-
Khaya senegalensis	5.69	-	-	-
Lannea acida	7.86	-	7.47	19.02
Lannea microcarpa	6.10	20.39	-	-
Lannea velutina	-	8.80	-	-
Pericopsis laxiflora	5.28	-	12.63	-
Piliostigma thonningii	4.45	-	5.48	5.39
Pterocarpus erinaceus	9.81	9.82	-	6.74
Senegalia gourmaensis	7.73	-	-	11.87
Senegalia macrostachya	-	8.15	-	5.22
Sclerocarya birrea	-	-	-	2.96
Sterculia setigera	-	-	-	10.85
Strychnos spinosa	4.78	-	-	4.73
Tamarindus indica	-	5.84	-	9.23
Terminalia avicennioides	-	-	14.28	-
Terminalia engleri	4.38	-	2.73	-
Terminalia laxiflora	8.75	20.42	-	-
Terminalia leiocarpa	-	-	14.79	11.62
Terminalia macroptera	-	8.38	11.50	-
Vachellia seyal	-	-	3.23	5.24
Vitellaria paradoxa	12.17	32.27	22.59	17.66
Vitex doniana	-	-	-	3.39
Xeroderiris stuhlmannii	-	-	6.34	-

Vitellaria paradoxa, *Terminalia laxiflora*, *Combretum glutinosum*, *Entada africana*, *Lannea velutina* (Table 3). In the Sudano-Sahelian zone, *Crosopteryx febrifuga*, *Vitellaria paradoxa*, *Terminalia avicennioides*, *Pericopsis laxiflora* and *Terminalia macroptera* were the most dominant in the Protected area whereas in the Unprotected areas, the most dominant was *Balanites aegyptiaca*, *Lannea acida*, *Vitellaria paradoxa*, *Combretum collinum*, *Sterculia setigera* (Table 2). However, *Vitellaria paradoxa* and *Combretum glutinosum* were common species found in each climatic zone and land use type.

3.2. Effect of climate, land use, habitats specific richness, and heterospecific density on the structural parameters of D. microcarpum

The analysis of the Kruskal Wallis test showed that the mean density ($\chi^2 = 85.864$; $P < 0.001$), mean diameter ($\chi^2 = 66.067$; $P < 0.001$), mean basal area ($\chi^2 = 94.043$; $P < 0.001$) and Lorey's mean height ($\chi^2 = 19.802$; $P < 0.001$) of *D. microcarpum* varied significantly ($P < 0.05$) between sites (Fig. 2). The highest mean density (53.38 ± 17.22 individuals/ha) was recorded in Sudano-Sahelian protected areas, while the lowest density (16.4 ± 8.55 individuals/ha^1) was observed in Sudanian unprotected areas. Regarding mean diameter, the highest value (23.87 ± 2.85 cm) was recorded in the Protected areas of the Sudano-Sahelian zone and the lowest value (16.61 ± 4.41 cm) was observed in the unprotected areas of the same climatic zone. For the basal area, the highest mean value (2.73 ± 1.28) was observed in the protected areas of the Sudano-Sahelian zone, and the lowest value (0.53 ± 0.54c) in the Unprotected areas of the Sudanian zone. In terms of Lorey's mean height, the lowest value (5.76 ± 0.95 m) was observed in the unprotected areas of the Sudano-Sahelian zone, and its highest value (6.13 ± 1.86 m) was observed in the protected areas of the Sudanian zone (Fig. 2).

The habitat heterospecific density caused a significant increase in the basal area, the density, and the diameter but lead a significant decrease in value of the Lorey's height (HL).

Habitat specific richness did not influence the basal area but caused a significant increase in the diameter and the Lorey's height. Rainfall significantly decreased the basal area, diameter and density, and increased the Lorey's height, although not significantly. Temperature did not influence the basal area and the Lorey's height but significantly influence the value of diameter and the species density (Table 4).

3.2.1. Population structure of Detarium microcarpum

The linear regression analyses of the diameter classes distribution revealed a negative slope in the different climatic zones and land use types (Table 5). The diameter classes of *D. microcarpum* individuals showed an irregular distribution of individuals, with a predominance of individuals of intermediate classes compared to those of extreme classes (Fig. 3). The predominance size class varied according to the climatic zones and land use type. The predominance class size was 15–20 in the protected areas, and 10–15 in the unprotected areas in the Sudano-Sahelian zone. In the Sudanian zone, the abundance size class was 10–15 in the protected areas, but there is a weak distribution in the unprotected areas (Fig. 3). Across the Sudanian zone, unprotected areas showed a weak correlation ($R^2 = 0.29$, $P = 0.1062$) between the number of individuals and their diameter classes. Similarly, both protected and unprotected areas within the Sudano-Sahelian zone showed a weak relationship ($R^2 = 0.26$, $P = 0.1303$ for protected areas and $R^2 = 0.39$, $P = 0.0556$ for unprotected areas). However, a notable exception was observed in the protected areas of the Sudanian zone, where a strong correlation ($R^2 = 0.54$, $P = 0.0159$) was found between the number of individuals and their diameter classes. Thus, the populations of *D. microcarpum* are unstable in the different climatic zones and land use types except for in the Protected areas of Sudanian zone (Table 5, Fig. 3).

The height classes distribution of the juvenile stratum revealed a negative slope for the different climatic zones and land use types, which indicate the dominance of individuals of small height classes. Besides, a positive slope was observed in the unprotected areas of the Sudano-Sahelian zone. In addition, the R^2 values with the non-significant p-values ($P > 0.05$) reveal an unsuccessful transition of juveniles from the lower classes to the higher classes, reflecting difficulties of survival in juvenile individuals (Fig. 4). Thus, the regeneration of *D. microcarpum* was characterized by unstable populations independent of the climatic zones and land use types.

4. Discussion

4.1. Effect of climate and land use on Detarium microcarpum stand diversity and composition

Overall, 102 woody species were recorded in *D. microcarpum* stands, divided into 79 genera and 28 families. This species richness represents 19.21% of the woody flora of Burkina. According to (Thiombiano et al., 2012), Burkina Faso contains 531 woody species.

Table 3
Jaccard's similarity of *Detarium microcarpum* stands according to the climatic zones and land use types.

Sites	SUPa	SPa	SSUPa	SSPa
SUPa	1			
SPa	0.4961	1		
SSUPa	0.3887	0.4619	1	
SSPa	0.2849	0.4438	0.4368	1

Legend: SUPa: Sudanian unprotected areas, SPa: Sudanian protected areas, SSUPa: Sudano-Sahelian unprotected areas, Sudano-Sahelian protected areas

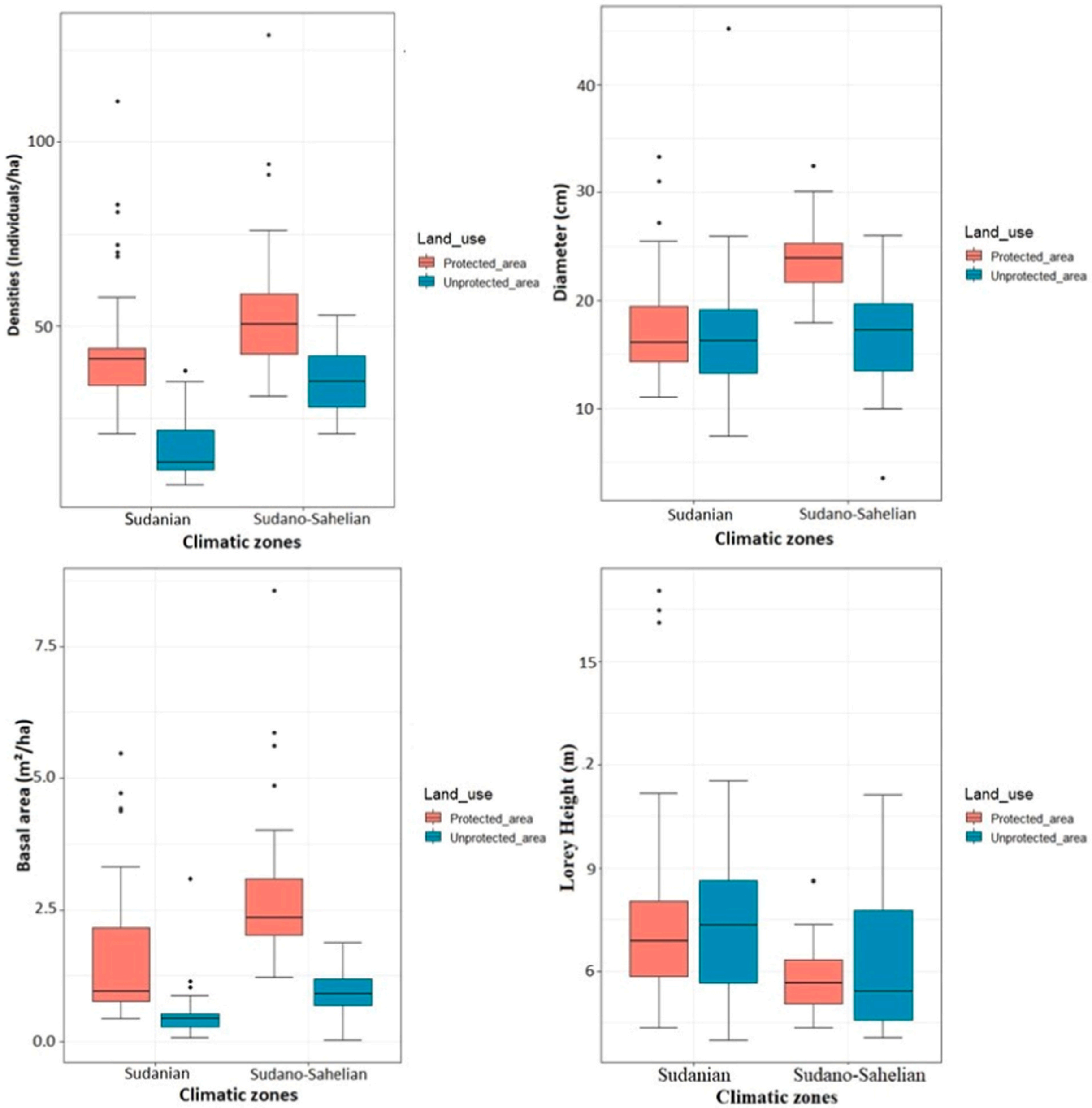

Fig. 2. Differences in *Detarium microcarpum* structural parameters between climate and land use types.

This result corroborates with Balima et al. (2020) which found 107 species divided into 73 genera and 35 families on the natural stand of *Afzelia africana* in the same climate zones. The dominance of Fabaceae, Anacardiaceae, Combretaceae, and Malvaceae families characterize dry climates (Tindano et al., 2015) and reveals the savanna character of these plant communities (Ganamé et al., 2019) associated with human pressures and climate pejoration (Lankoandé et al., 2017). Hill's diversity numbers revealed that species diversity decreased significantly from Sudanian to Sudano-Sahelian zone and from protected to unprotected areas. In each climatic zone, the highest species diversity of *D microcarpum* stands was recorded in Protected areas. Similar results were found by authors who demonstrated that Protected areas host higher diversity for stands of Combretaaceae species (Bognounou et al., 2009; (Ganamé et al., 2019)Ganamé et al., 2019)*; Afzelia africana* (Balima et al., 2020) and *Lannea macrocarpa* (Tinguéri et al., 2021) in Burkina Faso and *Strychnos spinosa* (Avakoudjo et al., 2022) in Benin. The significant difference in mean species and abundant species numbers between climate zones shows that the species richness increases with rainfall level in the Savanna ecosystem. Li et al. (2015) reported that human disturbance affected vegetation at the local scale and modified the ecosystem function. Balima et al. (2020) pointed out that agricultural land use contributes to the disturbance of species diversity. When comparing species richness according to the climatic zone and the land use type, the species richness gradually declines from Sudanian to Sudano-Sahelian zones and from protected areas

Table 4
Generalized linear models showing the effects of the biotic and abiotic factors *on Detarium microcarpum* structural parameters.

Variables	Estimate (β)	Std. Error	z value	Pr(>|z|)
Basal area				
(Intercept)	14.59	10.90	1.34	0.181^{ns}
Habitat heterospecific density	0.01	0.01	6.64	0.0000***
Habitat specific richness	0.01	0.014	1.15	0.252^{ns}
Rainfall	-0.01	0.00	-2.54	0.011*
Temperature	-0.45	0.37	-1.24	0.217^{ns}
Density				
(Intercept)	11.24	1.99	5.64	0.0000***
Habitat heterospecific density	0.01	0.00	28.82	0.0000***
Habitat specific richness	0.00	0.00	1.36	0.1743^{ns}
Rainfall	-0.00	0.00	-8.05	0.0000***
Temperature	-0.25	0.07	-3.65	0.0002***
Diameter				
(Intercept)	6.47	2.58	2.51	0.0121*
Habitat heterospecific density	0.00	0.00	1.29	0.1942^{ns}
Habitat specific richness	0.01	0.00	2.	0.0421*
Rainfall	-0.00	0.00	-2.55	0.0109*
Temperature	0.11	0.09	1.24	0.0216*
Lorey's height				
(Intercept)	0.33	4.16	0.08	0.9368^{ns}
Habitat heterospecific density	-0.01	0.00	-2.63	0.0085**
Habitat specific richness	0.02	0.01	2.89	0.0038**
Rainfall	0.01	0.00	1.67	0.0938^{ns}
Temperature	0.03	0.14	0.19	0.8510^{ns}

Legend: *** P < 0.001, ** P < 0.01, * P < 0.05. Std. Error: Standard Error; ns = non-significant

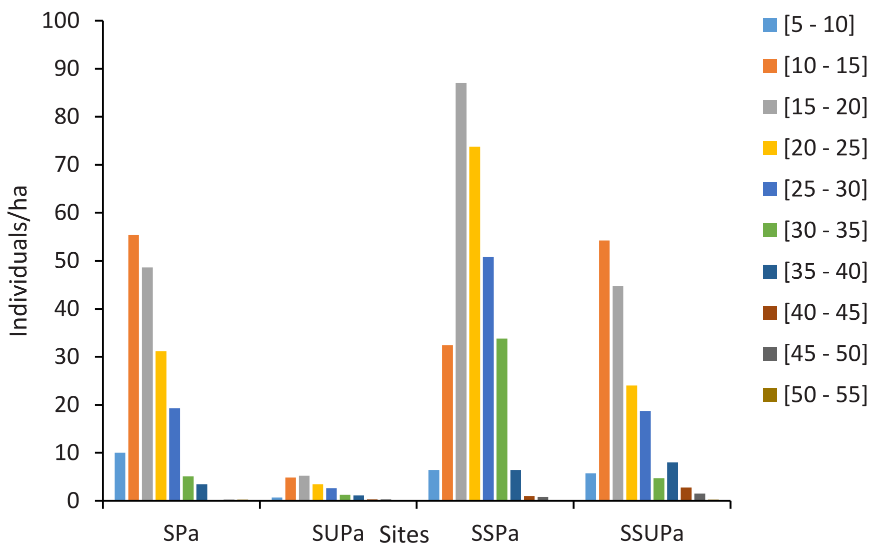

Fig. 3. Horizontal structure of adult stands of *Detarium microcarpum* Legend: Spa: Sudanian Protected areas, SUPa: Sudanian Unprotected areas, SSPa: Sudano-Sahelian Protected areas and SSUPa: Sudano-Sahelian Unprotected areas.

to unprotected areas. The findings of this study indicate that protected areas have a significant positive impact on species abundance. Following that, the higher diversity found in Protected areas highlights the great potential of these non-disturbed ecosystems in biodiversity conservation (Nacoulma et al., 2011). This proves the positive effect of protecting forests, especially in the tropics (Gray et al., 2016) like Burkina Faso. The higher Hill index in the Sudanian climatic zone is due to the Kou classified forest. This forest minimizes cropland expansion and pasture while still retaining natural forest characteristics (Yaovi et al., 2021) and reveals the influence of better management practices. Maryo and Wendawek (2014) reported that the low evenness can be attributed to excessive environmental disturbances, variable conditions for regeneration, and selective exploitation.

Jaccard's index values showed little similarity in species composition in *D. microcarpum* plant formations along the two climatic zones. The low values of the similarity index indicate a high β-diversity between populations and could be related to the climatic effect.

The higher IVI values of *D. microcarpum* obtained for the Sudano-Sahelian zone highlight the ecological importance of the species in this climate zone. On the contrary, the lower IVI values obtained on the Sudanian zone for the same species indicate that the species are

Table 5
Regression slope values of height class distributions (Juvenile) and diameter Class distribution (adults) of *Detarium microcarpum* stand according to climatic zones and land use types.

Climatic zones	Land use types	Regression parameters		
		Slope	R^2	P_value
Adult stratum				
Sudanian	Protected areas	-1.81	0.54	0.0159
	Unprotected areas	-0.57	0.29	0.1062
Sudano-Sahelian	Protected areas	-1.36	0.26	0.1303
	Unprotected areas	-1.24	0.39	0.0550
Juvenile stratum				
Sudanian	Protected areas	-0.29	0.06	0.7022
	Unprotected areas	-0.51	0.32	0.3230
Sudano-Sahelian	Protected areas	-0.90	0.05	0.7280
	Unprotected areas	0.39	0.29	0.3495

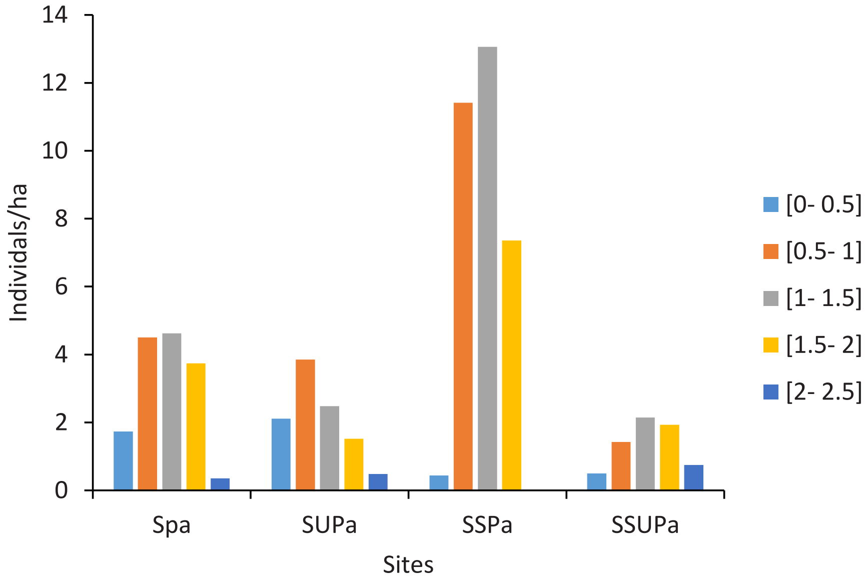

Fig. 4. Vertical structure of juvenile populations of *Detarium microcarpum* Legend: Spa: Sudanian Protected areas, SUPa: Sudanian Unprotected areas, SSPa: Sudano-Sahelian Protected areas and SSUPa: Sudano-Sahelian Unprotected areas.

not adapted to the humid zone (Lamy et al., 2021). This corroborates the results of Chejanovski and Wiens (2014) who explained that the climatic gradient influences the species niche. According to Zerbo et al. (2016), the low percentage of frequent species and the high rate of occasional and rare species implies on the one hand a great heterogeneity among plant communities of each climatic and land use condition with the human disturbance. Therefore, in the Sudanian and Sudano-Sahelian, the presence of some species (*Combretum glutinosum, Vittelaria paradoxa, Burkea africana, Piliostigma thoningii, crosopteryx februfiga, Entada africana, Terminalia laxiflora*) would be an indicator of sites suitable for *D. microcarpum* stand. In the Ivory Coast, it has been reported that, *Piliostigma thonningii* is an indicator of the presence of *D. microcarpum* on silty-clay soils (Fournier, 1991).

4.2. Effect of climate and land use on the structural parameters of Detarium microcarpum

Regarding the stand structure of *Detarium microcarpum*, the results show that the climate and land use have a significant influence on the structural parameters. The high densities of trees observed in the Sudano-Sahelian zones showed that the *D. microcarpum* is the savanna species that prefers low humidity. Lamy et al. (2021) pointed out that, the high density of *D. microcarpum* in the Sudano-Sahelian zone could be due to the autecology of the species. In addition, the Sudano-Sahelian climate zone characterizes a lower rainfall quantity than the Sudanian zone. This is in line with previous studies such as Nacoulma et al. (2011); Zerbo et al. (2018); Kabre et al. (2020); Houénon et al. (2022) showed that the differences in stand diversity in forests may be attributed to natural and anthropogenic disturbances. This leads to a high development of the structural parameters of the woody species in this zone, especially *D. microcarpum* which is an important fodder species. In protected areas, the density of *D. microcarpum* was significantly higher than in unprotected areas. Human pressure contributes to the fragmentation of plant formations (Sinadouwirou, Dicko, et al., 2022) which leads the loss of the biodiversity. This result corroborates with Nouhoun et al. (2019) and Kabré et al. (2020) who explain that human activities reduce the density of the species. In fact, the lower number of large trees observed in the land use area compared with the protected area may be explained by logging, which mostly affects individuals of large diameter.

Contrasting effects of abiotic and biotic factors were found, as temperature and precipitation have mainly negative effects on the species dendrometric parameters, while habitat heterospecific density and richness show positive effects. This finding corroborates with (Atanasso et al., 2019) who find that the heterospecific tree density influences the structure of *Afzelia africana* individual trees in the Pendjari Biosphere (Benin). The mean diameter, mean height, mean density, and basal area values were higher in the Sudano-Sahelian than in the Sudanian zone. This may be due to the climatic regime in the Sudano-Sahelian which favour the growth of the species. This corroborates with Amoako and Gambiza (2021) who pointed out that the regime of the climate influence the diameter size of *Anogeissus leiocarpa* Baill. in Guinea savannah of Ghana. In addition, The high population density found in this zone may be due to the quality of the soil which influences the symbiotic relationship between the roots of Leguminosae and mycorrhizal fungi (Raddad et al., 2005; Houénon et al., 2022).

The difference in the basal area between the protected and unprotected areas may be attributed to disparity in the surrounding species composition, degree of disturbances, age of trees, and the influence of the climate. Kacholi, (2019) pointed out that the species composition influences the basal area of the species. The low basal area values in the unprotected area were related to high accessibility due to the nearby population's lack of enough protection (Lamy et al., 2021) and illegal logging (Sinadouwirou et al., 2022). Consequently, the conservation of *D. microcarpum* is not sustainable.

The Habitat heterospecific density, Habitat species richness, temperature, and Rainfall influence the structure of *D. microcarpum* population at different levels. The negative impact of rainfall and temperature on the density and basal area of *D. microcarpum* indicates that the two variables have a contrasting influence on the recruitment and growth of the other species. However, the higher rainfall decreases the temperature at the special scale (Du et al., 2019; Rodrigo, 2022) and influences the richness of the species and the basal area (Bognounou et al., 2009; Premavani et al., 2014). These results indicate that the decrease in diameter is related to the increase in tree competition. According to Traoré et al. (2022), rainfall is one of the main climate variables which affect the species' population status.

Concerning population structure, rainfall is the main abiotic variable affecting the structure of *D. microcarpum*. This suggest that an increasing in rainfall can disturb the recruitment process of *D. microcarpum* juveniles. Traore et al., (2022) found that the density of the *Faidherbia albida* species which is the savannah species was influenced by the rainfall. Ostonen et al. (2011) and Mensah et al. (2020) pointed out that climate variation affect several characteristics of adult tree species such as the timing of leaf growth, the duration of the growing season, and the intensity of stress experienced by the trees in their natural stand. Likewise, the growth rate of the tree trunk is linked with the level of the precipitation and temperature, which increase the photosynthesis rate and, then, cambial activity (Schaffner, 2017).

The negative effect of habitat heterospecific density on the Lorey's mean height can be explained by the competition of the species with other species occurred in the same habitat. This can be related to the competition for light and nutrients. According to Aubréville and Trochain, (1937), *D. microcarpum* is a medium size tree (8 m −12 m), and taller trees can affect their competitiveness for light. In fact, the light is one of the most limiting resources that impact the growth of the species in the forest (Reuger et al., 2012; Azquez, 2020) and the increased light levels affected juvenile recruitment.

4.3. Effect of climate and land use on the population structure of Detarium microcarpum

The distributions of diameter and height classes of *D. microcarpum* reveals unstable populations in all the study areas. The instability of the species populations observed in the two climatic zones was generally characterized by a low number of small-diameter individuals and an irregularity of the transition in their size class distribution. The same trend was found by Kouyaté (2005); Houénon et al. (2022); Lamy et al. (2021); Agbo et al. (2018) who explain that the weakness of the forests' protection has caused the species threat. Bentsi-Enchill et al. (2022) pointed out that the overexploitation of the species in the Unprotected areas could be the reason for instability of the species structure and the lack of protection. Usually, when trees are logged without replacement, their structures decrease (Rivero et al., 2008). Similar results indicating the degradation of tree populations were reported by Traore et al. (2022) for *Faidherbia albida* and Mensah et al. (2020) for *Afzelia africana* in Africa. The lack of individuals in the larger size classes in the Sudano-Sahelian could be due to the illegal logging of bigger trees by the locals for timber and construction purposes. In fact, the local population depends on forest resources for firewood, building materials, livestock as well and income generation (Kouyaté, 2011; Dossa et al., 2020). This can reduce the availability of seeds and may thereby lead to a lack of regeneration (Thomas, 2006). According to Bouché et al. (2011), the elephant impacts affected negatively the recruitment of the species.

The size class distributions of the juvenile individuals suggest that the species are in a crucial stage of regeneration and recovering from disturbances.

The instability reported for the regeneration independent of the climate zone and the land use type indicated difficulties in recruitment and transition between the different classes in the species juvenile population (Zerbo et al., 2023). This instability would be linked to the pressures that the species faces, leading to its poor regeneration and then constitutes a threat to its survival. Bationo et al. (2001) pointed out that human pressure and the bushfire impacted the recruitment of the *D. microcarpum* juvenile species. In addition, Sinadouwirou et al. (2022) explained that the seed of *D. microcarpum* has a natural germination difficulty compared to the other species due to the tegument dormancy. Besides, according to the same authors, the low individuals number observed in the size class 0–0.5 could be also explained by bushfires which affected the fruit germination capacity due to burning. In addition, land clearing and tree density reduction for agricultural purposes may be detrimental to the seedling establishment and, hence, threaten the species

(Fandohan et al., 2011). The illegal logging of *D. microcarpum* for fire wood also contribute to the reduction of mature trees density, influencing the species fruits and seeds production. In fact, previous studies showed that *D. microcarpum* wood was highly appreciated by the population in particular by the women because of its high flame intensity (Agbo et al., 2017; Kouyaté, 2005). The fruits harvest reduce seed potential of edible tree species. Indeed, Taïta (2003) stated that species whose fruits and/or seeds are consumed often face regeneration issues. This is in line with the findings of authors who reported that the fruits of *D. microcarpum* are highly valued and consumed by the local populations (Agbo et al., 2020; Dieng et al., 2019; Dieng et al., 2016; Kouyaté, 2005). This study suggests that protecting *D. microcarpum* populations within Protected areas does not guarantee successful species recruitment across all size classes.

5. Conclusion

The floristic diversity and composition of *D. macrocarpum* natural stands vary according to the climatic zones and the land use types. Climate patterns and land use type influenced the structural parameters of and the population trend of the *D. microcarpum stand*. The degradation of the species stands structure and diversity due to land use have significant implications for biodiversity conservation related to the target 15 of the sustainable development goals. This study indicated that *D. microcarpum* has unstable populations and specific protection actions must be enforced to avoid full harvesting to ensure the recruitment of the species. It would be preferable to develop a good policy for integrating the species into the agroforestry system. To ensure the sustainable use of the species, it is crucial to implement institutional and managerial policies including the local population which could contribute to preserving the multipurpose species.

CRediT authorship contribution statement

Adama Taonda: Writing- original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation and Conceptualization. **Issouf Zerbo:** Writing- Original draft, Visualization, Validation, Software, Methodology, Data curation, Conceptualization and draft editing. **Anny Estelle N'Guessan:** Visualization, Methodology, Formal analysis and conceptualization. **Innocent Charles Emmanuel Traoré:** Vizualization, Formal analysis, Data curation, Writing - review editing, Supervision and Project administration. **Justin N'Dja Kassi:** Writing review and editing, Visualization, Validation, Supervision, Project administration.

Declaration of Competing Interest

This article is an original research and the authors declare that they have known competing financial interest or personal relationships that could have appeared to influence this work.

Data availability

Data will be made available on request.

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Consent for publication

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Appendix A. List of woody species across climatic zones and land use types

Famillies	Genera	Species	Sudanian climate zone		Sudano Sahelian climate zone	
			Protected areas	Unprotected area	Protected area	Unprotected area
Anacardiaceae	Anacardium	*Anacardium occidentale* L.		X		
Anacardiaceae	Lannea	*Lannea acida* A.Rich.	X	X	X	X
Anacardiaceae	Lannea	*Lannea microcarpa* Engl. & K.Krause	X	X		X
Anacardiaceae	Lannea	*Lannea velutina* A.Rich.	X	X	X	
Anacardiaceae	Mangifera	*Mangifera indica* L.	X	X		X
Anacardiaceae	Ozoroa	*Ozoroa insignis* Delile	X	X		

(*continued on next page*)

(*continued*)

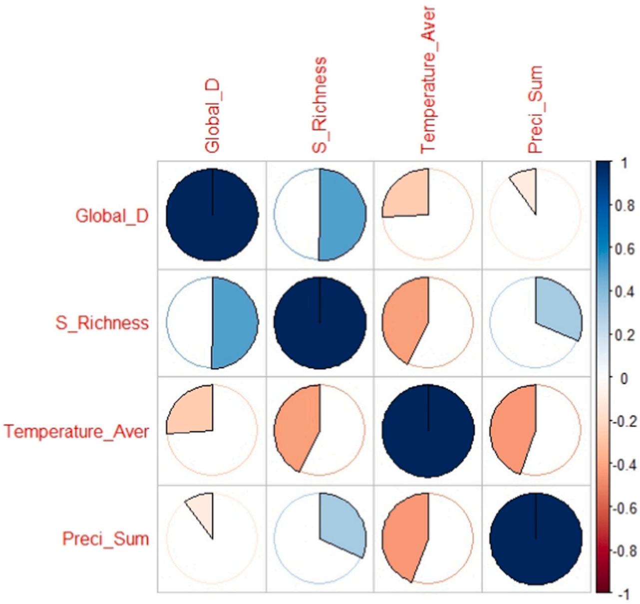
Famillies	Genera	Species	Sudanian climate zone		Sudano Sahelian climate zone	
			Protected areas	Unprotected area	Protected area	Unprotected area
Anacardiaceae	Sclerocarea	*Sclerocarya birrea* Hochst.				X
Annonaceae	Annona	*Annona senegalensis* Pers.	X	X	X	X
Annonaceae	Hexalobus	*Hexalobus monopetalus* Engl. & Diels	X	X		
Apocynaceae	Ancylobotrys	*Ancylobothrys amoena* Hua	X			
Apocynaceae	Calotropis	*Calotropis procera* (Aiton) Dryand.		X	X	
Apocynaceae	Holarrhena	*Holarrhena floribunda* T.Durand & Schinz	X			
Apocynaceae	Londolfia	*Londolfia heudelotii* A.DC.	X	X		
Apocynaceae	Saba	*Saba senegalensis* (A.DC.) Pichon	X	X		
Apocynaceae	Tacazzea	*Tacazzea apiculata* Oliv.	X			
Arecaceae	Borassus	*Borassus aethiopum* Mart.		X		
Arecaceae	Elaeis	*Elaeis guineensis* Jacq.	X	X		
Bignoniaceae	Sterospermum	*Stereospermum kunthianum* Cham.	X	X	X	X
Capparaceae	Capparis	*Capparis fascicularis* DC.	X		X	
Celastraceae	Gymnosporia	*Gymnosporia senegalensis* Loes.			X	
Chrisobalanaceae	Parinari	*Parinari curatellifolia* Planch. ex Benth.	X			
Combretaceae	Combretum	*Combretum adenogonium* Steud.ex A.Rich.	X		X	
Combretaceae	Combretum	*Combretum collinum* Fresen.	X	X	X	X
Combretaceae	Combretum	*Combretum glutinosum* Fresen.	X	X	X	X
Combretaceae	Combretum	*Combretum micranthum* G. Don			X	X
Combretaceae	Combretum	*Combretum molle* R.Br. ex G.Don	X			
Combretaceae	Combretum	*Combretum nigricans* Leprieur ex Guill. & Perr.	X			
Combretaceae	Combretum	*Combretum paniculatum* Vent.			X	X
Combretaceae	Guiera	*Guiera senegalensis* JFGmel.				X
Combretaceae	Terminalia	*Terminalia engleri* Gere & Boatwr.	X		X	X
Combretaceae	Terminalia	*Terminalia leiocarpa* Baill.	X	X	X	X
Combretaceae	Terminalia	*Terminalia avicennioides* Guill. & Perr.	X		X	
Combretaceae	Terminalia	*Terminalia laxiflora* Engl.	X	X	X	
Combretaceae	Terminalia	*Terminalia macroptera* Guill. & Perr.	X	X	X	
Combretaceae	Terminalia	*Terminalia mollis* Malawson	X			
Delleniaceae	Tetracera	*Tetracera alnifolia* Willd.	X			
Ebenaceae	Diospyros	*Diospyros mespiliformis* Hochst. ex A.DC.	X	X	X	X
Fabaceae	Afzelia	*Afzelia africana* Pers.	X	X	X	
Fabaceae	Aganope	*Aganope stuhlmannii* (Taub.) Adema	X	X	X	
Fabaceae	Albizia	*Albizia zygia* (DC.) JF Macbr.	X			
Fabaceae	Bernilia	*Bernilia grandiflora* (Vahl)Hutch.&Dalziel	X			
Fabaceae	Burkea	*Burkea africana* Hameçon.	X	X	X	
Fabaceae	Cassia	*Cassia sieberiana* DC.	X	X	X	
Fabaceae	Daniella	*Daniella oliveri* Hutch. & Dalziel	X	X		
Fabaceae	Detarium	*Detarium microcarpum* Guill. & Perr.	X	X	X	X
Fabaceae	Detarium	*Detarium senegalense* JFGmel.	X			
Fabaceae	Dichrostachys	*Dichrostachys cinerea* (L.) Wight & Arn.	X			
Fabaceae	Entada	*Entada africana* Guill. & Perr.	X	X		
Fabaceae	Erythrina	*Erythrina senegalensis* DC.		X		
Fabaceae	Isoberlinia	*Isoberlinia doka* Craib & Stapf	X		X	
Fabaceae	Ormocarpum	*Ormocarpum pubescens* (Hochst.) Cufod.	X			
Fabaceae	Parkia	*Parkia biglobosa* (Jacq.) R.Br. ex G.Don	X	X		
Fabaceae	Pterocarpus	*Pterocarpus lucens* Lepr. ex Guill. & Perr.	X			
Fabaceae	Pericopsis	*Pericopsis laxiflora* (Benth. ex Baker) Meeuwen	X		X	
Fabaceae	Philenoptera	*Philenoptera laxiflora* (Guill. & Perr.) Roberty			X	X
Fabaceae	Piliostigma	*Piliostigma reticulatum* (DC.) Hochst.	X		X	X
Fabaceae	Piliostigma	*Piliostigma thonningii* (Schumach.) Milne-Redh.	X		X	X
Fabaceae	Prosopis	*Prosopis africana* (Guill. & Perr.) Taub.	X	X		X
Fabaceae	Pterocarpus	*Pterocarpus erinaceus* Poire.	X	X	X	X
Fabaceae	Senegal	*Senegalia gourmaensis* (A.Chev.) kyal. $Boatwr			X	X
Fabaceae	Senegalia	*Senegalia dudgeonii* (Craib) Kyal. & Boatwr.	X			X
Fabaceae	Senegalia	*Senegalia gourmaensis* (A.Chev.) Kyal. & Boatwr.	X	X	X	X
Fabaceae	Senna	*Senna singueana* (Delile)			X	X
Fabaceae	Tamarindus	*Tamarindus indica* L.	X	X	X	X
Fabaceae	Vachellia	*Vachellia seyal* (Delile) PJHHurter			X	X
Fabaceae	Vachellia	*Vachellia sieberiana* (DC.) Kyal. & Boatwr.		X	X	
Lamiaceae	Gmelina	*Gmelina arborea* Roxb.		X		

(*continued on next page*)

(*continued*)

Famillies	Genera	Species	Sudanian climate zone		Sudano Sahelian climate zone	
			Protected areas	Unprotected area	Protected area	Unprotected area
Lamiaceae	Tectona	*Tectona grandis* LF	X			
Lamiaceae	Vitex	*Vitex doniana* Doux	X	X	X	X
Loganiaceae	Strychnos	*Strychnos spinosa* Lam.	X	X	X	X
Malvaceae	adansonia	*Adansonia digitata* L.	X			X
Malvaceae	Bombax	*Bombax costatum* Pellegr. & Vuillet	X	X	X	X
Malvaceae	Ceiba	*Ceiba pentandra* (L.) Gaertn.	X			
Malvaceae	Cola	*Cola cordifolia* (Cav.)R. Br.	X			
Malvaceae	Grewia	*Grewia rotii* DC.	X	X		
Malvaceae	Grewia	*Grewia lasiodiscus* K. Schum.	X			
Meliaceae	Azadirachta	Azadirachta indica A.Juss.		X		
Meliaceae	Khaya	*Khaya senegalensis* A. Juss.	X			
Moraceae	Ficus	*Ficus crocata* Mart. ex Miq.	X		X	
Moraceae	Ficus	Ficus thonningii Blume				X
Moraceae	Ficus	*Ficus sycomorus* L.				
Myrtaceae	Eucalyptus	*Eucalyptus camaldulensis* Dehnh.	X	X		
Ochnaceae	Lophira	*Lophira lanceolata* Van Tiegh. Ex keay		X		
Olacaceae	Ximenia	*Ximenia americana* L.	X		X	X
Phyllanthaceae	Bridelia	*Bridelia micrantha* (Hochst.) Baill.	X		X	X
Phyllanthaceae	Fluggea	*Fluggea virosa* (Roxb.ex Wild.) Royle.	X		X	
Phyllanthaceae	Hymenocardia	*Hymenocardia acida* Tul.	X	X		
Phyllanthaceae	Margaritaria	*Margaritaria discoidea* (Baill.) GLWebster	X			
Polygalaceae	Securidaca	*Securidaca longepedunculata* Fresen.	X			
Rhammaceae	Ziziphus	*Ziziphus spina-christi* (L.) Willd.			X	X
Rubiaceae	Crosopteryx	*Crosopteryx febrifuga* (Afz ex G.Don)Benth	X	X	X	
Rubiaceae	Feretia	*Feretia apodanthera* Delile	X		X	
Rubiaceae	Gardenia	*Gardenia aqualla* Stapf & Hutch.	X			
Rubiaceae	Gardenia	*Gardenia erubescens* Stapf & Hutch.	X	X	X	X
Rubiaceae	Gardenia	*Gardenia ternifolia* Schumach. & Thônn.	X	X		
Sapindaceae	Allophyle	*Allophylus africanus* P.Beauv.	X			
Sapindaceae	Bligia	*Blighia sapida* KDKoenig	X			
Sapotaceae	Manilkara	*Manilkara obovata* (Sabine & G.Don) JHHemsl.	X			
Sapotaceae	Pouteria	*Pouteria alnifolia* (Baker) Roberty	X			
Sapotaceae	Vitellaria	*Vitellaria paradoxa* CFGaertn.	X	X	X	X
Sterculiaceae	Sterculia	*Sterculia setigera* Delile	X	X		X
Zygophyllaceae	Balanites	*Balanites aegyptiaca* (L.) Delile	X	X	X	X

Appendix B. correlogram of the explanatory variable based on Pearson correlation



Legend: Global_D = habitat heterospecific density; S_Richness = habitat-specific richness, Temperature_Aver =mean annual temperature; Preci_Sum = Precipitation

Colored proportions reflect the values of the correlation coefficients.

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