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Abstract Climate variability added to anthropogenic pressures leads to habitat fragmentation, degradation and loss of forest ecosystem resources in Burkina Faso. Studying vegetation structure and woody species composition is important in monitoring vegetation dynamics for efficient forest management. This study was carried out to characterize woody vegetation along a climatic gradient. Stratified sampling according to four vegetation types was conducted in 120 plots in two protected areas. The plot size was 30 m × 30 m in savannas and 50 m × 10 m in gallery forests. In each plot, all woody species with a diameter at breast height (*DBH*) ≥ 5 cm were systematically identified and measured. Diversity indices, structural parameters and species importance values were calculated and compared among the sites and vegetation types. Linear discriminant analysis (LDA) was used to characterize each vegetation type in each climatic zone. The species diversity, tree density and basal area of woody species increased significantly along the climatic gradient from north to south. Discriminant analysis identified two vegetation types: open vegetation (shrub savannas and tree savannas) with moderate species richness and structural characteristics and closed vegetation (woodland savannas and gallery forests) with higher species richness and structural characteristics. The size class distribution showed that irrespective of the climatic zone, each vegetation type has a stable structure. Compensation among species in different diameter classes does not allow the effect of the climatic gradient between the two sites on the diameter class size distribution to be observed. This study revealed that climate is the main driver influencing the diversity of woody species rather than the site-specific conditions at the two sites. In addition to climate, site ecological conditions affect the structural parameters. The results provide a rational basis for planning and management decisions to ensure the sustainable use of resources in the two protected areas.

Keywords savanna · human activities · conservation · vegetation types · stand distribution

Abbreviations

CD	Crown diameter
GBH	Girth at breast height
HL	Lorey's mean height
LDA	Linear discriminant analysis
IVI	Importance value index

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TBR Tapoa-Boopo reserve
BKCF Boulon Koflandé classified Forest.

Introduction

Savannas are characterized by the co-existence of woody plants and grasses, with the horizontal and vertical spatial arrangement of trees creating a heterogeneous biotic environment (Fisher et al. 2013). West African savanna ecosystems are undergoing severe changes in their vegetation composition and species cover due to the impact of human activities and land use intensification effects under changing climatic conditions (Zerbo et al. 2016). Indeed, African savannas represent the most important ecosystems for people practising stock breeding and agriculture and provide non-timber forest products (NTFP) for multiple purposes (Nacoulma et al. 2011; Zizka et al. 2015). In recent years, the increasing human population and the consequent overexploitation of parklands related to increased livestock density and the extension of agricultural lands or a shortening of fallow periods have caused a dramatic change in savanna vegetation (Bouko et al. 2007; Zerbo et al. 2016; Jakubka et al. 2017). Climate deterioration combined with human activities, such as grazing, agricultural land use and fire, leads to habitat fragmentation and the degradation of savanna ecosystems (Bouko et al. 2007; Gnoumou et al. 2011). These ongoing activities threaten biodiversity and subsequently lead to the loss of species (Clerici et al. 2007). This situation has enormous ecological, economic, and social consequences for people's life (Diouf et al. 2002). Thus, the protection of savannas is essential for the protection of biodiversity to ensure the availability of natural resources for the subsistence and cash incomes of rural people in the future (Nacoulma et al. 2011). However, better conservation management depends primarily on the understanding of the specific factors and root causes responsible for these degradation processes (Traoré et al. 2012). Several studies have shown that the distribution, structure and composition of savanna vegetation depend on climate, habitat, herbivore, fire and land use effects (Hahn-Hadjali et al. 2006; Zerbo et al. 2016; Jakubka et al. 2017).

Woody species play an important role in the functioning of ecosystems and provide goods and services for rural populations (Nacoulma et al. 2011). However, some studies have reported that the degradation of savanna ecosystems is more noticeable among woody species, which are a more permanent component of the savanna vegetation than herbaceous species (Mbayngone et al. 2008a, b). Assessments of woody species, such as floristic composition and structure studies, are essential in view of their value in terms of understanding the extent of plant diversity in forest and savanna ecosystems (Dikaso and Tesema 2016). Studying the distribution and dynamics of woody species is necessary to identify important elements of plant diversity, protect threatened and economic species and monitor the status of specific forests (Ssegawa and Nkuutu 2006). Therefore, there is an urgent need to study the diversity and structure of African savanna ecosystems in general and those of Burkina Faso in particular.

The aim of this study was to compare the woody vegetation characteristics of two protected areas along a climatic gradient in Burkina Faso. The specific objectives were (i) to assess the effect of climate on the diversity and structural characteristics of the woody species in the different vegetation types and (ii) to discriminate habitat groups in relation to environmental variables in the study area.

Material and methods

Study areas

The study was carried out in Burkina Faso along a climatic gradient in two protected areas, namely, Tapoa-Boopo Reserve (TBR) and Boulon-Koflandé Classified Forest (BKCF). In this study, protected areas are defined as those that are clearly classified with appropriate legal status by public authorities with the aim of ensuring the protection of natural resources as well as ecosystem functions and services (Traoré et al. 2012). TBR is geographically located in eastern Burkina Faso, while BKCF occurs in western Burkina Faso. Climatically, TBR is located in the Sudano-Sahelian zone, and BKCF occurs in the Sudanian zone (Fig. 1). According to Dipama (2010), the Sudano-Sahelian zone is characterized by a short rainy season from June to October (4–5 months) and a long dry season (7–8 months). The mean annual rainfall ranges from 600 to 900 mm, and the mean monthly temperatures range from 20 to 30°C. In the Sudanian zone, the rainy season lasts from May to October (5–6 months). The mean annual rainfall often exceeds 1,100 mm, and the mean monthly temperature ranges from 20 to 25°C. The widespread vegetation types in the two protected areas are tree and shrub savannas.

Sampling design and data collection

Prior to the start of the field work, four vegetation types (shrub savannas, tree savannas, woodland savannas and gallery forests) were identified as the main vegetation types in each protected area based on previous studies in Burkina Faso (Soulama et al. 2015; Gnoumou et al. 2016). The types of vegetation were discriminated according to the Yangambi nomenclature of African vegetation types (Aubreville 1957). To achieve this, the vegetation map of each study area was used to select the number of plots defined per vegetation type through a random sampling scheme in each vegetation type. The geographic coordinates of the plots were noted and projected onto the study area map using GPS. In each protected area, ecological data were collected from 60 plots whose size varied according to the vegetation type. Inventories were conducted in square plots with a size of 900 m^2 (30 m ×30 m) in the savannas (Bouko et al. 2007; Mbayngone et al. 2008a) and rectangular plots of 500 m^2 (50 m × 10 m) in the gallery forests (Sambare et al. 2011). These plot sizes are widely used for woody vegetation sampling in West African savannas and generally meet the minimum area requirements of the Braun-Blanquet approach. The 60 plots were shared between the four vegetation types. Within each vegetation type, data collection consisted of recording and identifying all woody species, measuring their crown diameter (*CD*), total height and diameter at breast height (*DBH*). Species and family names were identified following Thiombiano et al. (2012). A measuring tape was used to measure the girth at breast height (*GBH*, at height 1.3 m), which was then converted to *DBH* using the following formula:

$$DBH = \frac{GBH}{\pi}$$

For multi-stemmed individuals, the *DBH* is derived from the quadratic mean of the *DBH* of all stems using the following formula:

$$DBH = \sqrt{\sum di^2},$$

where *di* is the diameter of the different stems. The height of each individual was measured using a clinometer.

Data analysis

Species richness and diversity

The species richness or taxonomic richness of an ecosystem is the number of species or taxa that can be found without considering the number of individuals or the biomass of each taxon (Kindt and Coe 2005; Zerbo et al. 2016). To assess species richness in this study, the number of species and mean number of species per plot were computed per vegetation type in each climatic zone. Species richness is often insufficient in terms of comparing the diversity of two communities because it does not consider the relative abundance of each species (Mbayngone et al. 2008a). For a better understanding of plant community structure and composition, we therefore used a combination of three diversity indices that take into account the relative abundance of different species (Bognounou et al. 2009). The Shannon index (*H*), Simpson's diversity index (*D*) and Pielou's evenness (*E*) were calculated according to the following formulas:

$$H = -\sum_{i=1}^{s} pilnpi$$

and

$$H = \sum_{i=1}^{s} pilnpi,$$

where *s* is the total number of species in the community (richness) and *pi* is the relative abundance of the *i*th species in a plot.

$$D = \sum_{i=1}^{s} \frac{Ni(Ni-1)}{N(N-1)},$$

where *Ni* is the number of individuals of the *i*th species and *N* is the total number of species in the vegetation type. *D* = 0 indicates high diversity, and 1 indicates low diversity.

$$E = \frac{H}{lnS},$$

where *H* is the Shannon diversity index and *S* is the total number of species in the community (richness). This index is widely employed to measure biological diversity (Magurran 2004; Bognounou et al. 2009). Its value approaches 0 when the vegetation type is

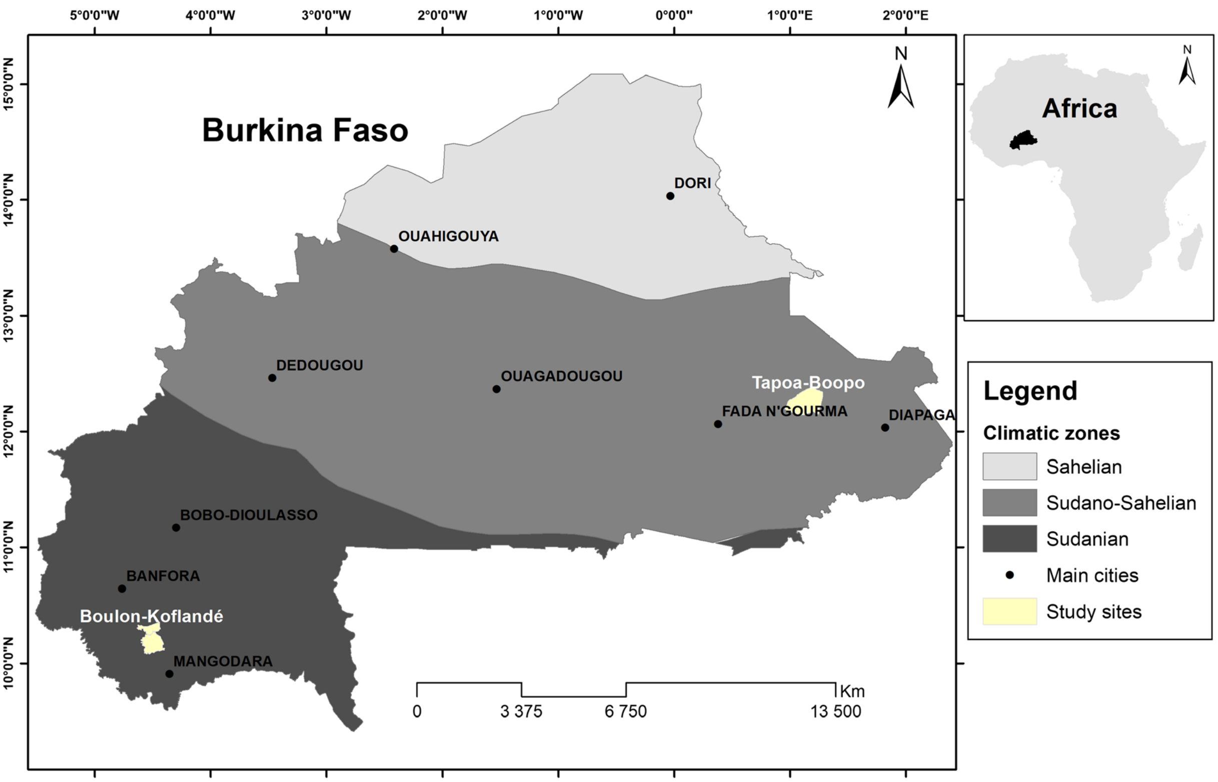


Fig. 1 Location of the study area.

highly dominated by one species and 1 when the individuals are distributed equitably among the species (Kent and Cooker 2003).

To assess the similarity among the climatic zones and types of vegetation (β diversity), the Sørensen similarity index was computed. Sørensen's coefficient of similarity was calculated based on presence/absence data for each species. It varies from 0 to 1. A value close to 1 indicates greater similarity between sites, hence a low diversity β (Magurran 2004).

The importance value index (*IVI*) was calculated for each species. This index, which integrates relative dominance, relative frequency and relative density, characterizes the place occupied by each species within the vegetation compared to that of other species (Mbayngone et al. 2008a, b). The *IVI* of a species is calculated as follows:

$$IVI = relative\ dominance + relative\ frequency + relaive\ density$$

IVI

$$Relative\ dominance = \frac{100 \times total\ basal\ area\ of\ a\ species}{total\ basal\ area\ of\ all\ species}$$

$$Relative\ frequency = \frac{100 \times Frequency}{\sum of\ all\ frequencies}$$

$$Relative\ density = \frac{100 \times number\ of\ individuals\ of\ the\ species}{total\ number\ of\ individuals}$$

Population structure

The following dendrometric parameters were computed for each vegetation type:

Mean tree diameter according to the formula: $d = \left(\frac{1}{k}\sum_1^k di^2\right)$, where k is the number of individual trees within the vegetation type and di is the diameter at breast height of each tree (cm)

Tree density, which indicates the number of tree individuals per hectare

Basal area (G) according to the formula

$$G = \frac{\pi}{4s} \sum_{i=1}^{n} \frac{di^2}{10^4},$$

where s is the area of a plot (0.09 ha) and di is the diameter at breast height of each tree (cm)

Lorey's mean height (HL, in m):

$$HL = \frac{\sum_{i=1}^{n} gihi}{\sum_{i=1}^{n} gi},$$

where gi = basal area ($m^2 \cdot ha^{-1}$).

To establish the size-class distributions (SCDs) of each vegetation type, all individuals ($DBH \geq 5$ cm) were grouped into diameter classes of 5 cm. The observed diameter SCD was adjusted to the three parameters (a, b, c) of the theoretical Weibull distribution (Johnson and Kotz 1970), which has the density function:

$$f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} exp\left\{-\left(\frac{x-a}{b}\right)^{c}\right\}$$

where x = tree diameter, a = location parameter (threshold), b = scale or size parameter linked to the central value of diameters, and c = shape parameter of the structure. The Minitab software version 14 was used for this analysis.

Separate one-way analyses of variance were used to compare the different variables (diversity indices and structural characteristics) among the vegetation types and climatic zones. The comparison tests were preceded by the Shapiro-Wilk normality test to check the normality of the data. Data were normalized using log transformations (Lankoandé et al. 2016) when the data were not normally distributed. *Post hoc* analysis of variables showing significant differences was carried out using Tukey's honestly significant difference (*HSD*) test. Linear discriminant analysis (LDA) was used with SPSS software to identify the ecological characteristics that discriminate the four vegetation types. The statistical analysis and diversity calculations were carried out with R v. 3.3.3. The 'Biodiversity R' (Kindt and Coe 2005) and 'Rcmdr' (Fox 2017) packages were used to calculate the diversity indices and perform the analysis of variance.

Results

Species richness, diversity and composition

Overall, 98 woody species distributed into 28 families and 67 genera were identified in the two protected areas. Among them, 60 species grouped into 20 families and 40 genera were identified in TBR. The floristic survey conducted in BKCF identified 69 woody species distributed into 24 families and 56 genera. The most common family in TBR was Combretaceae (57.88%), followed by Fabaceae (18.01%). The dominant family occurring in BKCF was Combretaceae (25.22%), followed by Rubiaceae (17.75%) and Fabaceae (9.81%).

Species richness increased along the climatic gradient from the Sudano-Sahelian to the Sudanian zone (Table 1). The mean species number per plot showed that the Sudanian zone is more diverse than the Sudano-Sahelian zone ($F_{[1;120]} = 18.89$; $P < 0.001$). The mean specific richness of the woody species is higher in BKCF than in TBR (Table 1).

Considering the vegetation type, we found that the number of species per plot varied significantly between gallery forests ($F_{[1;30]} = 33.3$; $P = < 0.001$) and woodland savannas ($F_{[1;\ 30]} = 39.8$; $P < 0.001$) in the two climatic zones. However, the number of species was not significantly different between the shrub savannas ($F_{[1;30]} = 1.88$; $P = 0.18$) and the tree savannas ($F_{[1;\ 30]} = 2.53$; $P = 0.13$) in the two climatic zones. In the same climatic zone, the specific richness is higher in gallery forest and shrub savanna than in the two other types of vegetation (Table 1).

The analysis of variance revealed that the diversity indices, the Shannon diversity index ($F_{[1;120]} = 26.9$; $P < 0.001$), Simpson's diversity index ($F_{[1,120]} = 28.5$; $P < 0.001$) and Pielou's evenness ($F_{[1;120]} = 7.67$; $P < 0.001$), varied significantly among the climatic zones. The higher value of the Shannon index observed in BKCF than TBR suggests that the woody vegetation diversity was higher in the Sudanian zone than in the Sudano-Sahelian zone. Based on the values of the inverse of Simpson's index, it appears that the number of abundant species per vegetation type decreases across the climatic gradient from the Sudanian to the Sudano-Sahelian zone. The vegetation records from the Sudanian zone were more heterogeneous than those from the Sudano-Sahelian zone. The value of

Table 1 Species richness and diversity indices according to the vegetation types within each climatic zone; *H* – Shannon's diversity index, *D* – Simpson's diversity index, *E* – evenness

Climatic zone	Items	Shrub savanna	Tree savanna	Woodland savanna	Gallery forest	Overall	*P*
Sudanian	Species richness	5.07 ± 1.94a	6.94 ± 2.08a	19.38 ± 6.10b	15.5 ± 4.68b	12.99 ± 7.68a	< 0.0001
	H (bits)	1.21 ± 0.40a	1.60 ± 0.34b	2.54 ± 0.49c	2.36 ± 0.38c	2.02 ± 0.66a	< 0.0001
	D	0.61 ± 0.16a	0.73 ± 0.10a	0.89 ± 0.05b	0.86 ± 0.06b	0.79 ± 0.14a	< 0.0001
	Evenness	0.71 ± 0.11a	0.75 ± 0.09a	0.70 ± 0.12a	0.71 ± 0.10a	0.72 ± 0.11a	0.52
Sudano-Sahelian	Species richness	4.29 ± 2.17 a	6.22 ± 1.20ab	8.22 ± 1.64b	11.00 ± 3.51c	7.83 ± 3.88b	< 0.0001
	H (bits)	0.98 ± 0.49a	1.35 ± 0.26ab	1.63 ± 0.33bc	1.88 ± 0.33c	1.49 ± 0.54b	< 0.0001
	D	0.50 ± 0.21a	0.65 ± 0.11ab	0.71 ± 0.13bc	0.78 ± 0.07c	0.66 ± 0.19b	< 0.0001
	Evenness	0.70 ± 0.13a	0.64 ± 0.12a	0.65 ± 0.15a	0.64 ± 0.12a	0.66 ± 0.13b	0.329

Superscript letters indicate significant differences according to ANOVA. Numbers with the same letters indicate that there is no significant difference.

Pielou's evenness index was higher for the plant communities in the Sudanian zone than those in the Sudano-Sahelian zone (Table 1).

The comparison of the diversity indices among vegetation types at the two sites showed higher values of the Shannon diversity index and Simpson's index in BKCF compared to TBR. These indices varied greatly between gallery forests and woodland ($P < 0.001$) in the two protected areas.

The results of the Sørensen similarity index revealed low to moderate similarity between the different vegetation types in the two climatic zones (Table 2). The greatest similarity (48.25) among vegetation types was observed between the tree savannas in the Sudanian zone and the woodland savannas in the Sudano-Sahelian zone. However, within the same climatic zone, there is a strong similarity (> 50%) among the four types of vegetation (Table 2).

According to the *IVI*, the woodland savannas and gallery forest in the two climatic zones are characterized by *Anogeissus leiocarpa* and *Mitragyna inermis,* respectively. The shrub and tree savannas of the Sudano-Sahelian zone are dominated by *Combretum nigricans*. In the Sudanian zone, *Combretum adenogonium* and *Isoberlinia doka* are the most abundant species found in shrub savannas and woodland savannas, respectively (Table 3).

Forest stand structure

The values of structural parameters, such as the mean diameter and Lorey's mean height of individuals, increased from the Sudano-Sahelian zone to the Sudanian zone. The mean diameter and Lorey's mean height were higher in gallery forest and woodland savannas compared to the other vegetation types in each climatic zone (Table 4).

The tree density and basal area increased significantly from the Sudano-Sahelian to the Sudanian zone ($F_{[1,120]} = 5.7$, $P = 0.001$ and $F_{[1;120]} = 8.63$, $P = 0.003$) and varied significantly among the vegetation types ($F_{[3,120]} = 35.92$; < 0.001 and $F_{[3;120]} = 12.91$, $P < 0.001$). The highest values of tree density and basal area were recorded in the woodland savannas and gallery forest at both sites, while the lowest values of tree density were recorded in shrub savannas in the Sudano-Sahelian zone (Table 4).

Discrimination of habitat groups

Linear discriminant analysis using the mean diameter, Lorey's mean height, tree density, basal area and the specific richness of a plot indicated the presence of two vegetation groups in the two climatic zones. The first axis opposed the shrub savanna and tree savanna groups versus the woodland savanna and gallery forest groups in the two climatic zones. Species richness, mean diameter, Lorey's mean height, mean basal area and density were positively correlated with this axis (Table 5). The second axis opposed the group of woodland savanna to that of gallery forest (Fig. 2).

The diameter class distribution of all woody vegetation types showed a reverse 'J'-shaped curve in both climate zones. The 5 to 30 cm diameter classes

Table 2 Sørensen similarity values between vegetation types according to climatic zone

Climatic zone	Type of vegetation	Sudano-Sahelian Shrub savanna	Sudano-Sahelian Tree savanna	Sudano-Sahelian Woodland savanna	Sudano-Sahelian Gallery forest	Sudanian Shrub savanna	Sudanian Tree savanna	Sudanian Woodland savanna	Sudanian Gallery forest
Sudano-Sahelian	Shrub savanna	1							
	Tree savanna	**64.52**	1						
	Woodland savanna	**66.67**	**74.7**	1					
	Gallery forest	45.83	48.98	43.48	1				
Sudanian	Shrub savanna	41.67	41.27	35	4.44	1			
	Tree savanna	32.14	36.62	34.09	7.55	**70.18**	1		
	Woodland savanna	40.58	48.25	47.52	15.15	**51.35**	**52.9**	1	
	Gallery forest	19.05	18.46	29.73	20.51	10.26	18.52	19.72	1

number in bold indicate strong similarity (≥ 50%) between vegetation types

are the most represented in the two climatic zones, while individuals of large diameter ($DBH > 30$ cm) are scarce in shrub savanna, tree savanna and woodland compared to gallery forest (Fig. 3). The values of the shape parameter 'c' for the adjustment of the Weibull theoretical distribution were between 0.85 and 1.45 (Fig. 3).

Discussion

Woody species diversity and composition

The 98 woody species recorded in the two climatic zones in this study represent 18.45% of the woody flora of Burkina Faso. Indeed, Nacoulma et al. (2018)

Table 3 Main species with high importance value index values according to vegetation type and climatic zone

Species	Relative dominance	Relative density	Relative frequency	IVI	Species	Relative dominance	Relative density	Relative frequency	IVI
Sudano-Sahelian					Sudanian				
Shrub savanna									
Combretum nigricans	39.08	35.22	19.44	93.75	*Combretum adenogonium*	20.36	26.16	16.18	62.70
Combretum glutinosum	19.27	31.77	21.30	72.34	*Acacia dudgeonii*	8.87	20.35	11.76	40.98
Acacia senegal	10.86	10.10	8.33	29.29	*Terminalia macroptera*	19.03	10.17	11.76	40.97
Tree savanna									
Combretum nigricans	9.21	25.00	9.46	43.67	*Isoberlinia doka*	29.56	11.71	7.21	48.47
Adansonia digitata	24.80	0.46	1.35	26.61	*Vitellaria paradoxa*	12.54	22.74	10.81	46.09
Acacia gourmaensis	8.85	11.57	5.41	25.83	*Pterocarpus erinaceus*	14.85	4.68	7.21	26.74
Woodland savanna									
Anogeissus leiocarpa	10.12	20.66	9.33	40.11	*Anogeissus leiocarpa*	17.28	14.19	7.34	38.81
Combretum nigricans	18.54	14.18	6.67	39.39	*Pterocarpus erinaceus*	10.35	6.87	5.41	22.63
Vitellaria paradoxa	18.60	12.87	7.33	38.81	*Cola cordifolia*	20.55	1.37	0.39	22.31
Gallery forest									
Mitragyna inermis	63.39	49.65	27.69	140.73	*Mitragyna inermis*	39.80	33.06	16.18	89.04
Anogeissus leiocarpa	12.29	10.56	13.85	36.70	*Pterocarpus santalinoides*	9.81	13.66	7.35	30.83
Combretum nigricans	3.83	11.27	12.31	27.41	*Syzygium guineense*	10.92	4.37	10.29	25.59

Table 4 Dendrometric characteristics according to the vegetation types within each climatic zone

Site	Items	Shrub savanna	Tree savanna	Woodland savanna	Gallery forest	Overall	*P*
BKCF	*Dm* [cm]	11.18 ± 2.39[a]	18.74 ± 6.47[b]	23.91 ± 3.12[c]	26.15 ± 5.8[c]	19.57 ± 10.42[a]	< 0.0001
	HL [m]	5.12 ± 1.27[a]	7.62 ± 2.41[b]	12.65 ± 3.83[c]	8.28 ± 2.04[b]	9.10 ± 4.21[a]	< 0.0001
	G [$m^2 \cdot ha^{-1}$]	2.95 ± 1.52[a]	15.13 ± 4.28[b]	24.60 ± 29.16[d]	25.20 ± 10.36[d]	163.04 ± 209.36[a]	< 0.0001
	Dens. [trees per ha]	207. 64 ± 64[a]	266.67 ± 82.03[ab]	504.12 ± 163.76[c]	426.62 ± 42.71[b]	358. 48 ± 187.60[a]	< 0.0001
TBR	*Dm* [cm]	10.68 ± 2.14[a]	14.21 ± 3.08[b]	21.90 ± 13.01[c]	18.11 ± 8.97[bc]	14.61 ± 5.14[b]	< 0.0001
	HL [m]	4.46 ± 0.91[a]	7.40 ± 1.77[b]	7.47 ± 2.02[b]	10.64 ± 1.17[c]	6.75 ± 2.42[b]	< 0.0001
	G [$m^2 \cdot ha^{-1}$]	1.96 ± 1.17[a]	8.02 ± 5.00[b]	10.12 ± 4.76[b]	20.17 ± 7.09[c]	101.18 ± 71.17[b]	< 0.0001
	Dens. [trees per ha]	168.44 ± 114.33[a]	254.81 ± 75.76[ab]	418.39 ± 178.99[c]	338.89 ± 91[bc]	324. 23 ± 153.86[b]	< 0.0001

Superscript letters indicate significant differences according to ANOVA. The numbers with the same letters indicate that there is no significant difference

Dm mean diameter, *G* basal area, *HL* [m] Lorey's mean height, Dens density

reported that the woody flora of Burkina Faso is composed of 531 species. Specifically, the flora of TBR represents 65.22% of the woody flora of the Pama Reserve in eastern Burkina Faso (Mbayngone et al. 2008b). A total of 53.22% of the woody flora of the Comoé Leraba Reserve was recorded in BKCF (Gnoumou et al. 2011). The lower species diversity recorded in our study could be due to the lower sampling intensity (Schmidt et al. 2005). The predominance of the Combretaceae and Fabaceae families, which characterize dry climates (Tindano et al. 2014), suggests that the species inventoried at both sites are typical of the Sudanian savanna (Mbayngone et al. 2008b). These plant families are the most common in West African savannas in general and in Burkina Faso savannas in particular (Ouédraogo et al. 2006). However, the presence of the Rubiaceae family, which characterizes humid climates, in the Sudanian zone showed the importance of the rainfall gradient in the species distributions.

Table 5 Correlations between species richness, dendrometric parameters and the axes of the linear discriminant analysis

	BCKF		TBR	
	Axis 1	Axis 2	Axis 1	Axis 2
Parameters	Correlation coefficient			
Species richness	0.92	0.09	0.67	0.55
Density	0.48	0.01	0.03	0.55
Basal area	0.64	−0.46	0.47	−0.96
Mean diameter	0.14	−0.48	0.77	0.33
Lorey's mean height	0.04	0.96	0.42	−0.33

The results of this study show that the species richness in the Sudanian zone is higher than that recorded in the Sudano-Sahelian zone, indicating that the species richness increases across the climatic zones. This is in agreement with the study by Bognounou et al. (2009), who reported an increase in species richness from the northern to the southern part of Burkina Faso. This increase in species richness might be due to an increase in rainfall from the Sudano-Sahelian to the Sudanian zone, reflecting the more arid climate in the Sudano-Sahelian zone. The same species diversity pattern along a climatic gradient was observed by Schmidt et al. (2005) in Burkina Faso. In West Africa, rainfall is a determining factor in terms of the establishment of plant species (Adomou 2005). By comparing the vegetation types within the same climatic zone and the same type of vegetation between the two climatic zones, we found that the species richness varied greatly only in gallery forest and woodland savannas. The high number of species in woodland savannas and gallery forests could be attributed to the particular ecological conditions of the microhabitats that favour the regeneration of these species. These results are in accordance with those of Zerbo et al. (2016), Bognounou et al. (2009) and Schmidt et al. (2013), who showed an increase in the number of herbaceous and woody species with increasing precipitation in the country.

The floristic diversity of woody vegetation is affected by the climatic gradient. The Sudanian zone

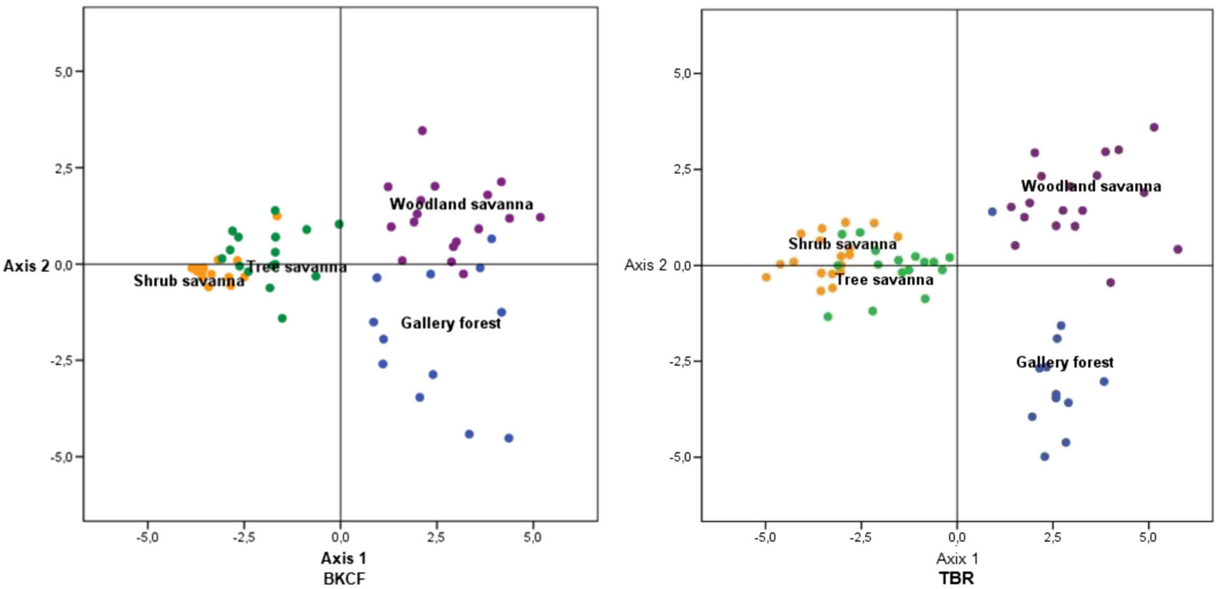


Fig. 2 Linear discriminant analysis showing the discrimination of plots on the basis of species composition and structural characteristics.

was more diverse than the Sudano-Sahelian zone. In addition to rainfall, overgrazing in TBR could explain the low diversity observed in this zone compared to that in BKCF. The distribution of rainfall and the intensity and frequency of anthropogenic disturbances are the main factors that influence the distribution of woody plant species (Tesfaye et al. 2014). The increase in the mean number of abundant species showed that the vegetation in BKCF in the Sudanian zone, which is less subject to anthropogenic pressures, benefits from favourable ecological conditions for the establishment and growth of several species (Bondé et al. 2013). This induces a higher heterogeneity of the plant communities in the Sudanian zone. The high values of Pielou's evenness revealed that the individuals of the dominant species have a relatively homogeneous distribution (Yélémou et al. 2015).

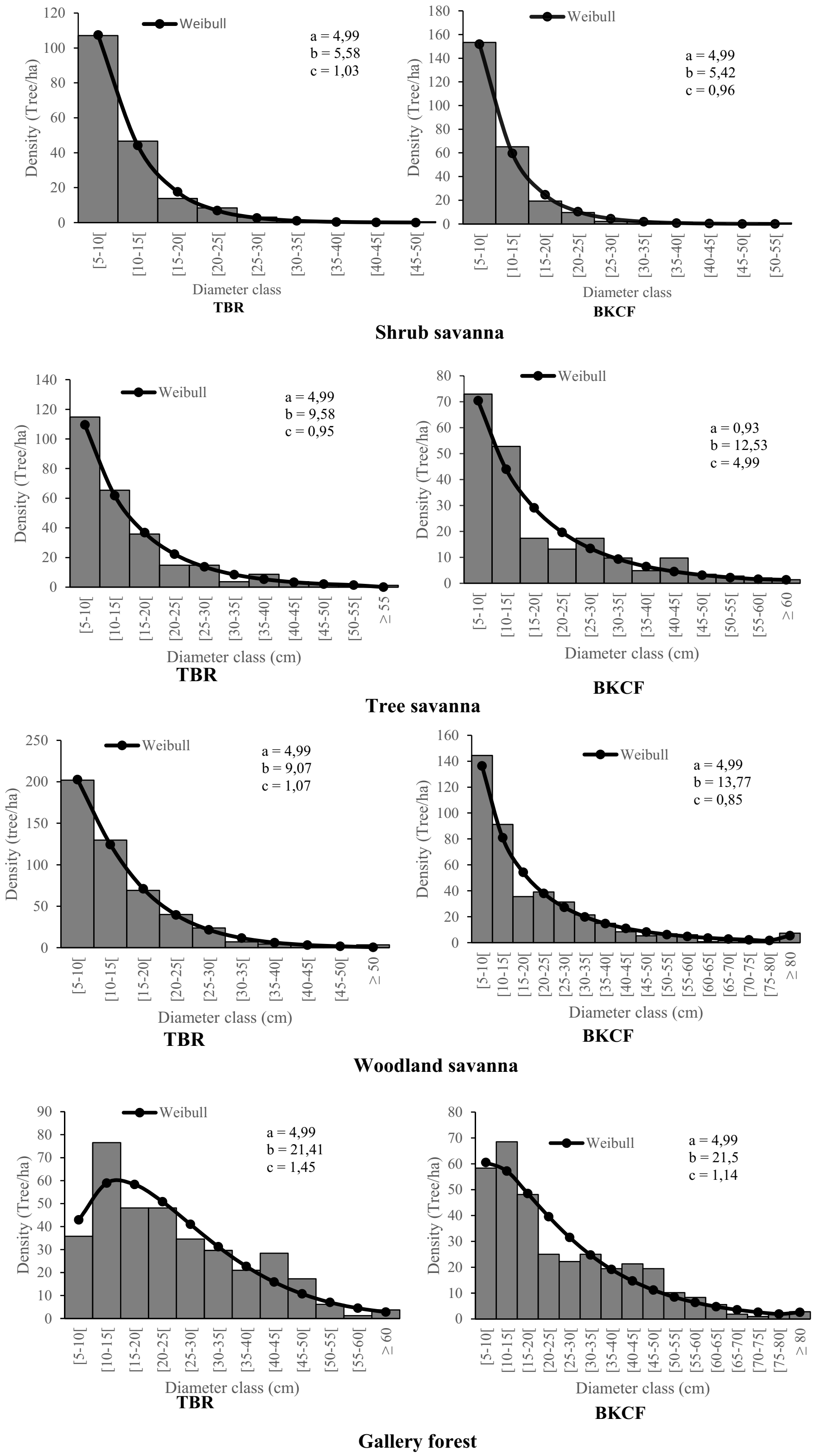
The similarity in woody plant species composition and abundance between the two climatic zones and vegetation types are low to moderate according to the values of the Sørensen index computed. This low to moderate similarity indicates the occurrence of high β diversity between the climatic zones and among the vegetation types and could be related to differences in climate and habitat conditions.

Forest stand structure and characterization of habitat groups

A slight increase in structural parameters was found from the Sudano-Sahelian to the Sudanian zones. The mean diameter, mean height, tree density and basal area values were higher in the Sudanian zone compared to those in the Sudano-Sahelian zone. This result might be caused by the variability in the distribution of the precipitation. Indeed, extreme temperatures and rainfall are limiting factors that can substantially alter the tree growth rate (Toledo et al. 2011) and consequently decrease forest productivity. Variability in precipitation could also influence soil moisture and nutrient cycling (Assogbadjo et al. 2017), affecting the quality of available resources for plant growth. Many studies have reported that climate influences forest stand productivity, growth and species distributions (Toledo et al. 2011). In addition, the difference in structural characteristics at the two sites may be related to anthropogenic pressures. These results agree with those of Bognounou et al. (2009) and Assogbadjo et al. (2017), who noted an increase in structural characteristics with increasing rainfall and the negative effects of anthropogenic factors on structural characteristics.

The variation in species richness and structural characteristics indicated the presence of two vegetation

Fig. 3 Diameter class size distribution of the four vegetation types in the two protected areas.



groups. The first axis of the linear discriminant analysis distinguished open vegetation (shrub savannas and tree savannas) from closed vegetation (woodland savannas and gallery forests). Along this axis, the shrub savannas and tree savannas are laid out successively from the left-hand side towards the right, opposing woodland savannas and gallery forest. The species richness, mean stem diameter, Lorey's mean height, density and basal area increase along this axis. At both sites, shrub savannas were characterized by low species richness, mean stem diameter, Lorey's mean height, density and basal area. Moderate species richness and moderate structural characteristics discriminated the tree savannas. Woodlands savannas and gallery forests were discriminated by having the highest species richness and structural characteristics values. The second axis, which opposed the woodland savanna group against that of gallery forest, might be influenced by the moisture gradient.

The reverse 'J'-shaped curve of the diameter class distribution in both climatic zones irrespective of the vegetation type indicates good regeneration potential (Traoré et al. 2012). This trend is a common feature of natural forests with active regeneration and recruitment. The reverse 'J'-shaped curve structure is explained by compensation among the species in the different diameter classes. Diameter classes that are lacking in some species are supplied by those of others (Bognounou et al. 2009; Traoré et al. 2012). This structure is ideal stable in terms of plant community stability because the community maintains itself (Gnoumou et al. 2011).

Conclusion

This study revealed that the diversity of woody species as well as the values of structural characteristics increased from Tapoa-Boopo Reserve in the Sudano-Sahelian zone to Boulon Koflandé Classified Forest in the Sudanian zone of Burkina Faso. The values of the species richness and diversity indices show that the plant communities of BKCF are more diverse than those found in TBR. These differences could be related to north-south precipitation variation and the intensity of anthropogenic disturbance. However, within the same study area, the diversity indices varied slightly among the different types of vegetation. The study also showed that structural characteristics and species richness can be used to discriminate woody vegetation groups. Among the discriminated groups, open vegetation was characterized by low to moderate species richness and structural characteristics. The highest species richness and structural characteristics were found in the closed vegetation. The structural parameters could be more affected by the climatic variation than the diameter class distribution of the woody plant communities. The compensatory effects among the different diameter classes indicate that all types of vegetation have a stable structure regardless of the climatic zone. This study provides a rational basis for planning and management decisions to ensure the sustainability of the use of natural resources in the two protected areas.

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Authors' contributions GM designed the field study, analysed the data and drafted the manuscript. PB and IO participated in the data collection and revised the manuscript. KD made the vegetation maps, selected the inventory plots and reviewed the manuscript. AT critically reviewed the different sections of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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