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RESEARCH PAPER **OPEN ACCESS**

Assessing tree diversity in cashew plantations: Environmental and agronomic determinants in buffer zones of Mont Sangbé National Park, western Côte d'Ivoire

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ABSTRACT

Within the framework of the rapid expansion of cashew plantations in West Africa, this research aims to investigate the floristic diversity of tree species associated with plantations positioned on the periphery of Mont Sangbé National Park in Côte d'Ivoire. The principal objective of this study is to assess the factors influencing this diversity, particularly cultivated areas, plantation age, and proximity to the MSNP. Surveys were conducted in three villages proximate to MSNP (Toulo, Gbeteman, Sorotonan), where 180 households were interviewed. Land and floristic data were collected via digital questionnaires, which were supplemented by field visits. A total of 272 plantations were documented, and 31 tree species were identified. Diversity indices-including species richness, Shannon, Simpson, and Pielou's evenness-were calculated using the Vegan package in R. Non-parametric tests (Kruskal–Wallis and Dunn's post hoc) facilitated the comparisons at the village level, while linear mixed models evaluated the effects of explanatory variables. Significant disparities were observed across the villages: Toulo exhibited the largest plantations and the highest floristic diversity, while Sorotonan demonstrated reduced species richness and increased dominance of species such as *Elaeis guineensis*. Mixed models substantiated that plantation area was the principal determinant of floristic diversity, with notable effects observed from 2 hectares onwards. Neither plantation age nor distance from the MSNP exhibited robust influences. The cultivated area predominantly shapes floristic diversity in cashew plantations surrounding MSNP. Integrated land management that encourages diversified agroforestry practices over larger plots appears critical for harmonizing sustainable agricultural production with biodiversity conservation.

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INTRODUCTION

In the rural areas of West Africa, the proliferation of perennial crops constitutes a significant factor in the transformation of agricultural and forest landscapes (Gnoumou *et al.,* 2020; Ruf and Zadi, 1998). Particularly in Côte d'Ivoire, cashew (*Anacardium occidentale* L.) cultivation has undergone substantial growth, especially in the northern and western regions, where it has emerged as a crucial source of income for smallholder farmers (Coulibaly and Coulibaly, 2024; Koulibaly *et al.,* 2016). Nonetheless, this expansion is correlated with significant alterations in the structure of agroecosystems, with limited documentation available regarding its impact on plant biodiversity, particularly within the buffer zones surrounding protected areas (Timite *et al.,* 2023; Yapo *et al.,* 2023).

The Mont Sangbé National Park (MSNP), situated in western Côte d'Ivoire, constitutes one of the remaining biodiversity sanctuaries within the Sudanian zone (Konan *et al.,* 2019; MINEDD, 2018). Nevertheless, the escalation of agricultural activities at its periphery, particularly through the proliferation of cashew plantations, elicits apprehension regarding the preservation of local floristic diversity (Konate *et al.,* 2020; Nnanga *et al.,* 2023). Although specific studies have indicated that agroforestry systems can uphold substantial levels of tree species diversity (Amani and Kieba, 2018; Ndiaye *et al.,* 2021), the determinants influencing this diversity-such as the size and age of plantations, as well as their proximity to protected areas-are not yet comprehensively understood.

In the context of the rapid expansion of cashew cultivation, how do the characteristics of plantations affect the diversity of tree species within the buffer zones adjacent to Mont Sangbé National Park? Furthermore, to what extent can these agricultural dynamics either detract from or support efforts in biodiversity conservation? The primary aim of this study is to assess the diversity of tree species connected with cashew plantations located on the outskirts of Mont Sangbé National Park, and to examine the environmental and agronomic factors that influence this diversity.

The study aims to systematically characterize the land structure of cashew plantations in proximity to the MSNP, with a particular focus on assessing the number of plantations per household and the areas under cultivation. It further intends to analyze the prevalence of tree species within these plantations to enhance understanding of local floristic composition. By comparing diversity indices across different villages, the research endeavors to identify spatial variations in arboreal biodiversity. Moreover, the study employs linear mixed models to evaluate the influence of three pivotal variables, plantation area, plantation age, and the distance to the MSNP, on floristic diversity. Ultimately, the findings will be contextualized within the framework of sustainable agro-ecosystem management.

MATERIALS AND METHODS

Study area

Located in the western region of Côte d'Ivoire, between the coordinates 7°51' and 8°10' north latitude and 7°03' and 7°23' west longitude, Mount Sangbé National Park (MSNP) spans an area of 97,554.37 hectares. The park extends across the departments of Biankouma, Touba, and Sifié (MINEDD, 2018). It primarily encompasses the former Mont Sangbé forest massif, designated as a state forest in 1945, which initially covered an approximate area of 105,000 hectares, including the Kangolo (24,000 ha) and Mont Boin (16,000 ha) massifs (Konan *et al.,* 2019). These three massifs were consolidated under decree no. 76-215 on February 19, 1976, to form Mount Sangbé National Park, named after its highest peak (Konan *et al.,* 2019). The primary economic activity for the communities residing in the vicinity of the MSNP is agriculture, with a predominance of food crops such as cassava, taro, rice, and maize.

Perennial crops are chiefly represented by plantations of cashew, coffee, cocoa, and rubber (Jeannot *et al.,* 2023). This study was conducted in three villages situated on the outskirts of the MSNP: Toulo (3.5

km), Gbeteman (8 km), and Sorotonan (4 km in a direct line from the MSNP) (Fig. 1). These sites were selected due to their proximity to the MSNP, enabling a detailed examination of the potential impact of cashew plantations on the territorial and ecological dynamics of the MSNP.

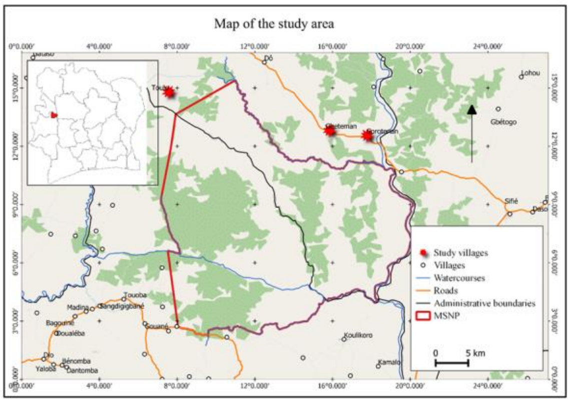

Fig. 1. Location of the study area

Data collection

In this investigation, household surveys were undertaken involving 180 households, systematically distributed across three villages (60 households per village) during the period from February to March 2024. Skilled enumerators executed data collection in conjunction with the Ivorian Office of Parks and Reserves (OIPR). Interviews were conducted with household heads, deemed to possess the most comprehensive knowledge regarding their cashew-plantation characteristics. These participants generally provided accurate data concerning the number of plots, plantation area, stand age, and proximity to MSNP. As these data are routinely recorded by Ministry of Agriculture agents for production forecasting, enumerators gathered them in strict compliance with established protocols, reflecting their perceived reliability.

The collection of data for the census of tree species within cashew plantations adhered to a three-step protocol. Initially, a focus group comprising producers was convened to assemble a comprehensive inventory of non-cashew tree species existing in the plantations. From this compilation, a digital questionnaire was devised, including photographs of the identified taxa (Kellenberger *et al.,* 2020). Subsequently, this questionnaire was administered to 180 randomly selected households using a tablet interface, which facilitated producers in accurately identifying species, documenting their names and counts, noting their presence within each plantation, and reporting the total number of plantations they managed (Berre *et al.*, 2022; Fritz *et al.*, 2015).

Ultimately, in instances where producers encountered challenges in estimating the number of trees of specific species, on-site inspections were executed within the plantations (Berre *et al.,* 2022). During these inspections, enumerators, in conjunction with the pertinent producers, conducted direct enumeration of the trees. This triangulated methodology guaranteed the precision and dependability of data concerning tree diversity within the cashew plantations.

The identification of species conformed to the standards set forth by the Flora of Arbonier (2009) and Hawthorne (2006).

Statistical analysis

Statistical characterization of cashew field areas and inter-village comparisons using non-parametric approaches

The research, utilizing a sample of 60 households per village, facilitated the computation of descriptive statistics regarding cashew field areas, aggregated by village. For each village, we determined the number of plantations, mean, median, standard deviation, interquartile range (IQR), and extreme values (minimum, first quartile [Q1], third quartile [Q3], and maximum).

Quartiles were estimated employing non-parametric methods to ensure robustness against outliers. The distribution of field areas was represented through boxplots using the ggplot2 package in R 4.4.2 version. To evaluate differences between villages, the non-parametric Kruskal–

Wallis test was employed, permitting rank-based comparisons without assuming normality (Dinno, 2015). When the Kruskal–Wallis test revealed significant differences, we conducted post hoc pairwise comparisons utilizing Dunn's test, with p-value adjustment via the Benjamini–Hochberg procedure to control the false discovery rate (Benjamini and Hochberg, 1995).

Quantitative assessment of biodiversity in cashew plantations using frequency, diversity indices, and non-parametric statistical approaches

We calculated species presence frequency within each village. For a given village j and species k, the presence frequency $freq_{jk}$ is defined as the proportion of sampling plots in which the species was recorded at least once ($count > 0$). This proportion is computed separately for each village–species pair. As a result, species presence frequency provides, for each species and each village, a value ranging from 0 to 1 that summarizes the consistency of tree occurrence across the sampling plots.

$$freq_{jk} = \frac{\#\{i | count_{ijk} > 0\}}{total\ surveys\ in\ village\ j}$$

$$= \frac{1}{n_j} \sum_{i=1}^{n_j} 1\,(count_{ijk} > 0)$$

where $1(\cdot)$ is the indicator function and n_j is the number of surveys for village j.

To visually represent the frequency of species presence in each village, we generated a heatmap using the ggplot2 package in R 4.4.2 version. In this graphical matrix, each cell corresponds to the intersection of a species and a village, and its color reflects the previously calculated presence frequency. This heatmap enables rapid identification of ubiquitous versus rarer species, as well as variations in species occurrence across villages.

Diversity indices facilitate a quantitative evaluation of the diversity of tree species within cashew plantations. These indices include not only species richness, the total count of distinct species, but also species evenness, which denotes the distribution pattern of individuals across the observed taxa. This dual perspective presents a more comprehensive depiction of biodiversity than simple species counts. The indices were calculated utilizing the Vegan package within the R 4.4.2 statistical environment (Oksanen, 2025).

Species richness S, obtained by

$$s = \sum_{i=1}^{S} 1(n_i > 0)$$

where n_i is the abundance of species i and $1(\cdot)$ is the indicator function.

Shannon diversity index H, defined by

$$H = -\sum_{i=1}^{S} p_i\, ln(_{pi})\ with\ p_i = \frac{n_i}{N}, N = \sum_{i=1}^{S} n_i$$

Simpson diversity index D, calculated as

$$D = 1 - \sum_{i=1}^{S} p_i^2$$

Pielou's evenness J, measuring the uniformity of individual distribution among species, given by

$$J = \frac{H}{ln(S)}\ for\ S > 1$$

The distribution of biodiversity indices, namely, species richness (S), Shannon index (H), Simpson index (D), and Pielou's evenness (J), was represented through boxplots for each village, effectively summarizing the central tendency and dispersion via medians, quartiles, and extreme values. To assess inter-village differences, a non-parametric framework was employed. The Kruskal–Wallis test was administered independently for each index to compare observation ranks, circumventing the assumptions of normality or homogeneity of variances (Dinno, 2015). Upon the observation of statistically significant results ($p < 0.05$), post hoc pairwise comparisons were executed utilizing Dunn's test, with p-value adjustments performed through the Benjamini–Hochberg procedure (Benjamini and Hochberg, 1995). This methodology ensures stringent control of the false discovery rate and facilitates a robust identification of village pairs demonstrating significant differences in biodiversity metrics.

Modeling the effects of environmental and agronomic factors on tree diversity in cashew plantations using linear mixed models

To evaluate the impact of environmental and agronomic factors on the floristic diversity within cashew plantations, linear mixed models (LMMs) were employed for three biodiversity indices: species richness, Shannon diversity index, and Simpson diversity index (Bolker *et al.,* 2009; Zuur *et al.,* 2009). The fixed effects comprised plantation age, cultivated area, and the distance to the boundary of MSNP. Each model incorporated a random intercept at the village level (random effect: 1 | Village) to account for the hierarchical structure of the data and spatial dependence among observations.

Model estimation was conducted employing restricted maximum likelihood (REML), facilitating comprehensive comparison across model specifications. Execution was implemented in R 4.4.2 utilizing the lme4 package (Bates *et al.,* 2015), while foundational assumptions, such as residual normality, homoscedasticity, and the absence of influential observations, were assessed using the performance package (Ludecke *et al.,* 2021). This methodology ensured statistical robustness and enhanced the reliability of ecological inferences derived from the models.

RESULTS

Cashew plantation distributions

A total of 272 cashew plantations were examined across the three study villages: 93 in Gbeteman (with an average of 1.55 plantations per household), 87 in Sorotonan (with an average of 1.45 plantations per household), and 92 in Toulo (with an average of 1.53 plantations per household). This distribution suggests that multiple households manage more than one cashew plantation, indicating a predilection for multi-plot management within the local agricultural framework.

Examination of plantation areas uncovered significant disparities among the villages (Fig. 2): Toulo demonstrated the highest mean (4.84 hectares) and median (5 hectares) field sizes, evidencing a predominance of extensive operations, whereas Gbeteman exhibited the lowest metrics (mean: 3.03 hectares; median: 2 hectares), with Sorotonan occupying an intermediate position. Standard deviations extended from 2.72 to 3.36 hectares, and a uniform interquartile range (IQR) of 3 hectares indicated consistent central variability across the villages.

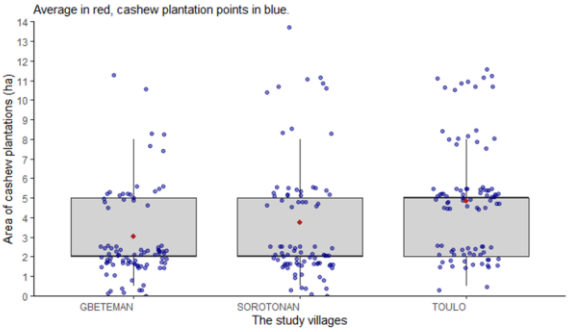

Fig. 2. Distribution of cashew plantation areas by village, including individual data points and mean values

Nonetheless, Gbeteman and Sorotonan displayed greater maximum values (14 hectares) compared to Toulo (11 hectares), suggesting the presence of isolated large-scale plantations.

The Kruskal–Wallis test ($H = 27.003$; $p = 1.37 \times 10^{-6}$) established the presence of statistically significant variations in plantation area across the villages. Subsequent post hoc pairwise comparisons conducted using Dunn's test, with adjustments made through the Benjamini–Hochberg procedure, demonstrated that Toulo possessed significantly larger plantation areas compared to Gbeteman and Sorotonan, between which no significant difference was observed.

Frequency-based patterns of tree species composition in cashew agroforestry systems

A comprehensive survey documented the presence of 31 distinct tree species across the cashew plantations located in the three villages (Fig. 3). The analysis of species frequency revealed significant ecological and cultural variations in species composition. In Toulo, African locust bean (*Parkia biglobosa* Jacq.) exhibited overwhelming dominance (80.4%), while yellow mombin (*Spondias mombin* L.) was more prevalent in Sorotonan (48.3%), and monkey bread tree (*Piliostigma thonningii* Schum.) in Gbeteman (49.5%). The oil palm (*Elaeis guineensis* Jacq.), an oil-bearing species, was prevalent across all three villages (55–65%), highlighting its local significance.

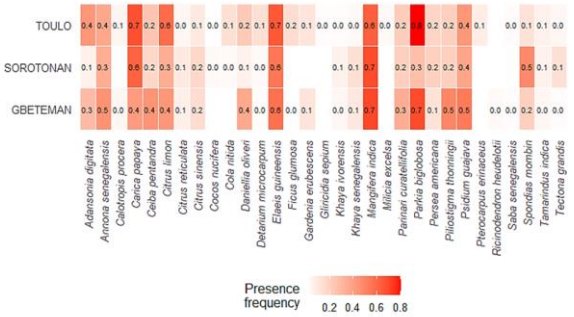

Fig. 3. Heatmap showing species presence frequencies across villages

African baobab (*Adansonia digitata* L.) exhibited a heterogeneous distribution pattern, characterized by a markedly low frequency in Sorotonan (6.9%) as opposed to higher frequencies observed in Gbeteman (29.0%) and Toulo (43.5%). Papaya tree (*Carica papaya* L.) was predominantly found in Sorotonan (62.1%) and Toulo (67.4%), whereas its presence was less pronounced in Gbeteman (41.9%). Mango tree (*Mangifera indica* L.) demonstrated widespread occurrence across all surveyed locales, with rates surpassing 63%, highlighting its significant role within local agroforestry systems.

Village-level variation in tree biodiversity within cashew agroecosystems: insights from Richness, Shannon, Simpson, and Pielou indices

The evaluation of floristic diversity indices for arboreal species within cashew plantations revealed significant variations among the three studied villages (Fig. 4). Sorotonan demonstrated lower species richness, with an average range of 5 to 6 tree species per plantation, in contrast to the 8 to 10 species observed in Gbeteman and 10 to 12 in Toulo. The Shannon diversity index (H) substantiated this pattern, displaying lower values in Sorotonan (1.2–1.6), and relatively higher values in Gbeteman and Toulo (>1.8), indicative of enhanced overall diversity within the latter two villages. The Simpson index (D) was similarly reduced in Sorotonan (0.50–0.80), reflecting pronounced dominance by a limited number of species, chiefly oil palm, whereas Gbeteman and Toulo exhibited elevated scores (0.80–0.95), suggesting a more equitable distribution of individual species. Pielou's evenness index (J) adhered to a comparable trend, with reduced values in Sorotonan (0.45–0.75) and increased values in Gbeteman and Toulo (0.75–1.00), reflecting a more uniform species distribution within cashew plantations.

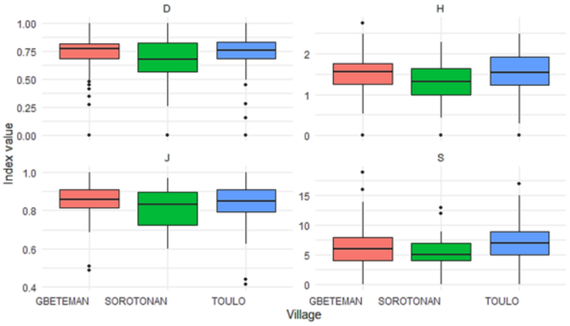

Fig. 4. Distribution of biodiversity indices across villages

Employing the Kruskal–Wallis statistical test, the analysis unveiled significant variations between villages in terms of species richness ($\chi^2 = 12.11$; $p = 0.0023$), Shannon diversity ($\chi^2 = 11.56$; $p = 0.0031$), and Pielou's evenness ($\chi^2 = 9.50$; $p = 0.0087$), whereas the Simpson index did not achieve statistical significance ($\chi^2 = 5.78$; $p = 0.0555$). These results indicate that, although there are differences in richness and abundance-weighted diversity among villages, the species dominance structure remains largely consistent.

Subsequent analyses utilizing Dunn's test, with adjustments made through the Benjamini–Hochberg procedure, revealed that Sorotonan exhibited a markedly lower species richness in comparison to both Gbeteman (Z= 2.51; p.adj = 0.018) and Toulo (Z= −3.36; p.adj= 0.0023), with no statistically significant difference observed between the latter two (p.adj= 0.386). Analogous patterns were noted for Shannon diversity and Pielou's evenness, corroborating a declining gradient of diversity and compositional uniformity from Toulo to Sorotonan. Conversely, no significant differences in the Simpson index were detected between villages following adjustment, indicating a relative constancy in species dominance across the locations.

Floristic structure in cashew agroforestry systems: effects of plot size, age, and spatial proximity

The application of linear mixed models (LMMs) to three biodiversity indices, Shannon diversity, species richness, and Simpson diversity, emphasized the significant influence of plantation area on the structuring of tree communities within cashew agroecosystems. In the Shannon diversity model (AIC= 432.4; see Table 1), the variance attributable to differences between villages (σ^2= 0.035) was markedly lower than the residual variance (σ^2= 0.239; see Table 2), indicating that most variability in biodiversity indices occurred at the plot level.

Table 1. Statistical summary

Statistique	Shannon	Richness	Simpson
AIC	432.4	1408.8	−163.4
BIC	508.1	1484.5	−87.7
logLik	-195.2	−683.4	102.7
Deviance	390.4	1366.8	−205.4
df.resid	251	251	251

Larger plantations (≥ 2 ha) were associated with significantly positive fixed effects (p < 0.001), indicating a substantial increase in species diversity. Conversely, the effects of plantation age and proximity to MSNP were more moderate and only partially significant.

The species richness model (AIC= 1408.8) corroborated this pattern, with inter-village variance contributing 12% to the overall variance and notable increases in species richness manifested across all area categories exceeding the reference level. Specifically, plantations of 2 ha (β= 2.19; t= 3.40), 5 ha (β= 2.91; t= 4.13), 8 ha (β= 4.18; t= 4.13), 11 ha (β= 3.29; t= 3.52), and 14 ha (β= 8.44; t= 5.63) exhibited significant enhancements, whereas age and proximity to MSNP were associated with negligible influences.

The Simpson model (AIC = −163.4) indicated an extremely low inter-village variance (σ^2 = 0.00119) and demonstrated that solely large plantations (≥ 5 ha) markedly increased species evenness, as evidenced by positive fixed effects (Table 3) for 5 ha (β= 0.093; t= 2.375), 11 ha (β= 0.141; t= 2.708), and 14 ha (β= 0.275; t= 3.284). Conversely, the age of plantations displayed an overall negative yet statistically insignificant effect (t ranging from-0.256 to −1.602), and the distance to MSNP, while characterized by negative coefficients (up to -0.225 at 0.75 km), failed to achieve statistical significance.

Table 2. Random effects

Groups	Parameter	Shannon		Richness		Simpson	
		Variance (σ^2)	Std. Error	Variance (σ^2)	Std. Error	Variance (σ^2)	Std. Error
Village	(Intercept)	0.03464	0.1861	1.211	1.101	0.001191	0.03451
	Residual	0.23885	0.4887	8.656	2.942	0.027034	0.16442

Collectively, these findings converge on a consistent conclusion: the extent of cultivated area serves as the predominant factor influencing diversity, richness, and evenness within tree species communities in cashew plantations, whereas the age of the orchard and its spatial location assume secondary roles.

Model diagnostics confirmed a rigorous adherence to statistical assumptions. In the case of the Shannon and Simpson models, standardized residuals conformed closely to the theoretical normal distribution, whereas the richness model exhibited slight leptokurtosis, albeit remaining suitable for parametric inference. Homoscedasticity analyses indicated consistent residual variance across all models, absent of funnel-shaped patterns or systematic trends. Despite the presence of a few outliers, variance dispersion remained stable, thereby affirming the validity of the homoscedasticity assumption crucial for reliable parametric testing.

Table 3. Fixed effects

Parameter	Shannon			Richness			Simpson		
	β	Std. Error	t-value	β	Std. Error	t-value	β	Std. Error	t-value
(Intercept)	2.065	0.587	3.520	9.775	3.531	2.768	0.860	0.195	4.409
13-year-old plantation	−0.356	0.296	−1.203	−1.032	1.784	−0.578	−0.025	0.099	−0.256
18-year-old plantation	−0.304	0.313	−0.972	−0.426	1.884	−0.226	−0.072	0.104	−0.689
23-year-old plantation	−0.505	0.305	−1.652	−1.483	1.840	−0.806	−0.164	0.102	−1.602
28-year-old plantation	−0.319	0.347	−0.919	−1.035	2.089	−0.496	−0.042	0.116	−0.370
04-year-old plantation	−0.751	0.305	−2.461	−3.351	1.838	−1.823	−0.109	0.102	−1.065
08-year-old plantation	−0.496	0.298	−1.666	−2.011	1.793	−1.121	−0.060	0.100	−0.599
2-hectare plantation	0.454	0.106	4.247	2.185	0.643	3.396	0.021	0.035	0.598
5-hectare plantation	0.679	0.117	5.797	2.910	0.705	4.127	0.093	0.039	2.375
8-hectare plantation	0.836	0.168	4.973	4.182	1.011	4.133	0.097	0.056	1.736
11-hectare plantation	0.856	0.155	5.513	3.287	0.935	3.516	0.140	0.052	2.708
14-hectare plantation	1.391	0.249	5.581	8.444	1.500	5.627	0.275	0.083	3.284
0.5 km from the MSNP	−0.365	0.700	−0.522	−1.319	4.218	−0.313	−0.089	0.235	−0.378
0.75 km from the MSNP	−1.035	0.568	−1.820	−6.826	3.424	−1.993	−0.225	0.191	−1.176
2 km from the MSNP	−0.620	0.506	−1.225	−3.965	3.048	−1.301	−0.102	0.170	−0.600
4 km from the MSNP	−1.002	0.506	−1.977	−5.585	3.051	−1.830	−0.202	0.170	−1.185
7 km from the MSNP	−0.763	0.507	−1.503	−4.251	3.055	−1.391	−0.195	0.170	−1.144
9 km from the MSNP	−0.573	0.505	−1.134	−3.541	3.042	−1.164	−0.110	0.170	−0.652
12 km from the MSNP	−0.757	0.502	−1.507	−4.332	3.026	−1.432			

Influence diagnostics demonstrated that the Shannon, richness, and Simpson models were generally resilient to extreme values. Only a limited number of observations, specifically, one plantation in the Shannon model and two in the Simpson model, showed notable influence, yet their impact was constrained and fixed-effect estimates remained stable, thereby reinforcing the reliability of statistical inferences.

DISCUSSION

The examination of 272 cashew plantations across the three surveyed villages revealed an unequal distribution of cultivated areas, indicating divergent land-use dynamics among the localities. Toulo was distinguished by significantly higher average and median plot sizes, indicative of the prevalence of large-scale agricultural operations. Conversely, Gbeteman exhibited the smallest field areas, whereas Sorotonan occupied an intermediate position.

These observations align with the findings of Coulibaly and Coulibaly (2024), who documented pronounced disparities in land tenure across villages within northern Côte d'Ivoire's cashew-producing regions.

Discrepancies in land area are particularly pertinent when evaluating the diversity of tree species within cashew plantations. Previous research, such as Timite *et al.* (2023), has illustrated that the size of plantations can significantly affect plant diversity, with larger plantations generally supporting a broader spectrum of tree species, either through deliberate conservation efforts or decreased land-use pressure. In the present study, the central variability in plot size indicates moderate heterogeneity, whereas the presence of extreme values (up to 14 ha in Gbeteman and Sorotonan) suggests the existence of isolated large plantations that may have distinctive roles in shaping or maintaining local biodiversity.

The floristic inventory executed in cashew plantations within the three villages identified 31 associated tree species, indicating significant arboreal diversity. This level of species richness corresponds to that reported by Nnanga *et al.* (2023) in cashew agroforestry systems in Chad, highlighting the capacity of such systems to incorporate a wide range of taxa. Nevertheless, presence frequency analysis disclosed marked ecological and cultural variations across the locations. In Toulo, African locust bean was predominant (80.4%), reflecting a local inclination towards multipurpose species, a trend also documented by Amani and Kieba (2018) in northwestern Côte d'Ivoire. Yellow mombin was more frequently encountered in Sorotonan (48.3%), whereas monkey bread tree prevailed in Gbeteman (49.5%), suggesting site-specific agronomic practices and traditional applications.

Certain species, notably oil palm, demonstrated an even distribution across all three villages, ranging from 55-65%, indicating their socio-economic importance within local agroforestry systems. This widespread occurrence, as also emphasized by Timite *et al.* (2023), underscores the species' contribution to farmers' adaptive strategies. In contrast, African baobab exhibited a more varied distribution pattern, with a low incidence in Sorotonan (6.9%) and increased presence in Gbeteman (29.0%) and Toulo (43.5%), which may be attributed to ecological factors or culturally influenced preferences. Fruit-bearing species such as papaya and mango trees were prominently represented, particularly in Toulo and Sorotonan, affirming their integration into agroforestry, as documented by Ndiaye *et al.* (2021).

Floristic diversity indices demonstrated notable differences among the three study villages. Sorotonan exhibited lower species richness, with an average of 5 to 6 species per plantation, in contrast to 8 to 10 in Gbeteman and 10 to 12 in Toulo. This variation aligns with Kéassemon *et al.* (2021), who underscored the impact of agroecological context and cultural practices on diversity within cashew orchards. The higher Shannon diversity values (>1.8) observed in Gbeteman and Toulo, relative to the lower values recorded in Sorotonan (1.2–1.6), further support these findings. Similarly, Simpson diversity scores were found to be lower in Sorotonan (0.50–0.80), indicating greater species dominance (particularly of oil palm), while Gbeteman and Toulo displayed higher scores (0.80–0.95), suggesting more balanced community compositions. These observations concur with Nnanga *et al.* (2023), who concluded that more diverse plantations tend to preserve more equitable floristic assemblages, often associated with agroforestry practices incorporating both utilitarian and voluntarily retained species. Pielou's evenness index mirrored this trend, with lower values in Sorotonan (0.45–0.75) and higher measurements in Gbeteman and Toulo (0.75–1.00), reflecting more homogeneous species distributions in the latter two villages.

The application of linear mixed models to assess biodiversity indices, such as Shannon, species richness, and Simpson, has substantiated the essential influence of plantation area on the organization of tree communities. In regard to the Shannon index, the lower inter-village variance ($\sigma^2 = 0.035$) compared to the residual variance ($\sigma^2 = 0.239$) suggests that the majority of variability is present at the plot level. The significantly positive fixed effects associated with larger plots (≥ 2 ha, $p < 0.001$) affirm that an increase in plantation size enhances species diversity. These results are consistent with the findings of Timite *et al.* (2023), which demonstrated that larger cashew plantations (>5 ha) possess greater floristic richness due to an enhanced capacity for species integration or retention.

The species richness model substantiated this relationship, highlighting significant gains across all size classifications exceeding the reference level, particularly at 5 hectares. A moderate inter-village variance (12%) indicates that plot characteristics rather than village-level factors predominantly influenced the differences observed. These findings align with Nnanga *et al.* (2023), who demonstrated that well-structured, larger plantations facilitate increased floristic richness. Conversely, plantation age and proximity to MSNP manifested marginal or non-significant effects on diversity, as supported by

Yapo *et al.* (2023), who noted that orchard age exerts a limited impact on vegetation diversity, particularly in the absence of active regeneration practices.

In conclusion, the Simpson index, which measures species evenness, demonstrated significant effects associated with larger plantation sizes, notably from 5 ha onwards. Positive fixed effects (e.g., β= 0.275 at 14 ha) suggested an improved distribution of individuals across species in larger plots. The exceptionally low inter-village variance (σ^2 = 0.00119) corroborated that this pattern was primarily local. Neither the age of the plantations nor their proximity to the MSNP exhibited significant effects. However, negative coefficients were identified for plots situated near the MSNP (e.g., −0.225 at 0.75 km). This is in alignment with findings by Koulibaly *et al.* (2016), who noted diminished floristic diversity near protected areas owing to usage limitations or increased anthropogenic pressure.

CONCLUSION

This research endeavor sought to evaluate the diversity of tree species associated with cashew plantations in three villages situated on the outskirts of MSNP, with specific consideration given to factors potentially affecting this diversity—specifically, plantation area, age, and proximity to the MSNP boundary. The findings disclose significant inter-village disparities in both land tenure structures and floristic compositions. These variations mirror unique agroecological and sociocultural dynamics that influence the species composition and structural framework of tree communities. The floristic survey identified 31 tree species associated with cashew plantations, revealing village-specific patterns of dominance reflective of both local preferences and ecological conditions. Diversity indices demonstrated greater species richness and increased evenness in certain villages, whereas others exhibited a higher dominance of a limited number of species, notably oil palm. These findings highlight the pivotal role of local agroforestry practices in either sustaining or reducing plant biodiversity within cashew-based production systems. The analysis of linear mixed models identified plantation area as the primary determinant of floristic diversity. Larger plantations were consistently correlated with heightened species richness, increased diversity, and more equitable distributions of species. Conversely, the age of the plantation and proximity to the MSNP exhibited only marginal or statistically non-significant impacts on the observed diversity. These findings collectively suggest a definitive conclusion: the strategic expansion of cultivated areas, alongside diversified agroforestry practices, serves as a critical mechanism for conserving and enhancing tree biodiversity within agricultural landscapes adjacent to MSNP. In contrast, neither the age of the orchard nor mere spatial proximity to protected areas suffices to ensure increased floristic richness. These results advocate for integrated landscape management strategies that harmonize sustainable agricultural production with biodiversity conservation objectives.

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