

CHARACTERISATION OF THE DEMOGRAPHIC AND SPATIAL STRUCTURES OF THREE NATURAL POPULATIONS OF *KHAYA SENEGALENSIS* IN CÔTE D'IVOIRE

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The ongoing destruction of savannas poses a grave threat to the survival of valuable tree species such as the African mahogany (*Khaya senegalensis*), which is of significant importance to local stands due to its timber and medicinal properties. This study aimed to assess the dendrometric, structural, and spatial characteristics of *K. senegalensis* stands in Côte d'Ivoire. Sampling was conducted in three sites with different characteristics: a well-preserved sacred forest (Kouassi-N'Dawa), a moderately degraded community forest (Koumokro), and a highly degraded community forest (Pouniakélé). Dendrometric variables were measured to reveal significant differences between these sites, and the different regeneration modes of the species were determined. The Weibull distribution was used to analyse stand structuring, and spatial analyses were performed to understand tree distribution in each stand. The analysis revealed that Kouassi-N'Dawa exhibited the highest tree density (40.7 trees ha⁻¹) and natural seedling density (47 seedlings ha⁻¹). No significant difference was observed between the three sites regarding basal area and stump sprout density. The diameter class distribution exhibited two distinct patterns: an inverted J-shaped distribution at Koumokro and Kouassi-N'Dawa, and a positively skewed distribution at Pouniakélé. The spatial distribution pattern of *Khaya senegalensis* was found to be aggregated, a property that may be useful for reforestation trials.

Keywords: Ecology, spatial distribution, forestry, sustainable management, vegetation dynamics

INTRODUCTION

As in many tropical countries, the economic development of Côte d'Ivoire depends heavily on its natural resources, whose exploitation or expansion leaves scars on natural ecosystems. These consequences are amplified by population growth and climate change. As with forests, savannas are also severely and negatively impacted by these phenomena. In savanna regions, anthropogenic pressures mainly come in the form of harvesting wood, leaves, bark, and roots of plants for growing daily needs, and more severely, land clearing and even complete deforestation. As a result, savanna ecosystems are being depleted at a rapid pace, which could significantly impact tree demographic structure, spatial distribution, and regeneration (Ehui et al. 1989, Wezel & Haigis 2000, Bamba et al. 2010, Goba et al. 2019), ultimately affecting the evolutionary potential of species. A thorough

understanding of the spatial and ecological structures of existing stands is therefore essential (Holl 2017, Hermoso et al. 2022). Structural attributes such as density, diameter and height class distribution of trees, and basal area provide insight into biodiversity management in ecosystems and enable comparisons between plant communities (Doucet 2003, McElhinny et al. 2005). As for the spatial distribution of trees, it describes how individuals are arranged in relation to one another within a stand. This distribution may be uniform, random, or aggregated (Clark & Evans 1954, Tilman et al. 2006, Muller-Landau et al. 2008), and it influences competition for resources, growth, and survival probability (Tilman et al. 2006, Reich et al. 2014). For instance, the spatial distribution of certain emblematic savanna species with a shading effect, such as *Khaya*

senegalensis, may favor the establishment of other woody species (Azihou 2013).

Khaya senegalensis (Desr.) A. Juss. (Meliaceae), a species native to African savannas, is classified as vulnerable (IUCN, 1998) due to overexploitation. It is widely used in both the timber industry and traditional medicine. Its characteristics make it a vital resource for local populations, who harvest various parts of the plant (Gaoue & Ticktin 2007), including leaves, bark, and roots for medicinal purposes. Such harvesting undermines the species' regeneration capacity. Furthermore, repeated cutting for charcoal production and other uses jeopardises the long-term survival of this species, which exists only in natural stands. These threats raise the issue of balancing resource conservation with meeting the daily needs of local communities. As a result, sustainable management of genetic resources is required, based on knowledge of the species' life traits in its natural populations.

In this context, sacred forests play a crucial role in the conservation of *K. senegalensis*. Managed by local communities, these areas are governed by strict rules limiting the exploitation of natural resources, thereby contributing to the preservation of both plant and animal species they shelter. For example, in Côte d'Ivoire, the sacred forests of Korhogo located in the Sudanian zone, protect endangered species through cultural taboos prohibiting wood cutting, hunting, and any form of agricultural activity within their boundaries (Gueulou et al. 2019).

The main objective of this study is to identify the parameters necessary for maintaining the species in its natural habitat. Specifically, the study aims to determine the availability of the resource and assess natural regeneration strategies, establish the demographic structure of the stands, and determine the species' spatial distribution model for *K. senegalensis* in three sites with contrasting environmental and management conditions.

MATERIALS AND METHODS

Study area

The present study was conducted in three distinct types of savannas (Sudanian, sub-Sudanian, and

Guinean) in Côte d'Ivoire. The Pouniakele site, situated in the far north of Côte d'Ivoire within the Bagoué region (between 6° 25' 53"–6° 31' 17" W and 10° 06' 47"–10° 16' 22" N), is classified as part of the Sudanian savanna zone, distinguished by the presence of two contrasting seasons. The region experiences an average annual rainfall of 1200 mm, with a mean annual temperature of 27 °C. The topography is characterised by plateaus, interspersed with hills or rocky domes, with elevations ranging from 400–600 m. The soil types present include lithosols, vertisols, and ferruginous soils (Beaudou & Sayol 1980). The vegetation is characterised by gallery forests, open forests, and wooded, shrubby, and grassy savannas (Guillaumet & Adjanohoun 1971). The site is further distinguished by the presence of trees, shrubs, pastures, and agricultural activities.

The Kouassi-N'Dawa site (Bondoukou department) is situated between 2° 53' 43"–2° 54' 24" W and 8° 06' 55"–8° 07' 52" N, within the sub-Sudanian savanna zone. The mean annual rainfall is 1400 mm, and the mean annual temperature is 26 °C. The region's climate is typified by a four-season pattern, with two dry seasons and two rainy seasons. The major dry season extends from November to March, while the minor dry season occurs from July to August. In contrast, the major rainy season extends from April to June, and the minor rainy season from September to October (Ouattara 2001). The topography of the region is characterised by undulating hills that reach elevations of up to 600 m (Guillaumet & Adjanohoun 1971). The soils are predominantly ferralitic, with hydromorphic soils prevalent in lowlands subject to temporary waterlogging. The vegetation is dominated by savannas and gallery forests (Tiebre et al. 2016). The sampling site is a sacred forest located on a hill, where human activities are strictly limited and forest management is focused on preserving cultural values.

The Koumokro site (Bocanda department, central-eastern Côte d'Ivoire) is a community forest situated between 4° 28' 52"–4° 29' 14" W and 6° 59' 54"–7° 00' 20" N. The region is characterised by a transitional climatic zone where the subtropical and humid tropical climates meet (Brou et al. 1998), resulting in four

distinct seasons, including two dry and two rainy seasons. The annual rainfall is approximately 1300 mm, while the mean annual temperature is 27 °C. The topography of the Koumokro site is predominantly gentle rolling plateaus, with elevations ranging from 200–350 m. The soils are remolded ferrallitic, moderately desaturated, and derived from quartzitic schists, which are rich in clay and possess good water retention capacity (Kouassi et al. 2010). The vegetation consists of savannas and gallery forests, and the local stand primarily engages in agriculture (Guillaumet & Adjanooun 1971).

Data collection

In each site, an exhaustive sampling was conducted and all *K. senegalensis* trees were georeferenced. Trees with a diameter at breast height (dbh) of ≥ 5 cm were included in the demographic and spatial structure analysis (Rabiou et al. 2015, Ouattara et al. 2016, Goba et al. 2021). For the regeneration study, three elementary plots of one hectare each (100 m $\times$ 100 m) were established at each site. All *K. senegalensis* individuals with dbh < 5 cm were recorded as seedlings (Goba et al. 2021).

Data analysis

Resource availability and regeneration strategy

To assess resource availability, tree density and basal area were calculated. Tree density was determined as the average number of trees per hectare across the three plots. Basal area (G , expressed in $\text{m}^2 \text{ha}^{-1}$) for each plot was calculated using the formula:

$$G = \frac{\pi}{4} \times \frac{\sum_{i=1}^n d_i^2}{s}$$

where d_i represents tree diameter, and s is the sampled surface area (in hectares). The mean basal area across the three plots was computed for each site.

For seedlings (dbh < 5 cm), different regeneration modes (semi-natural, root suckers, or stump sprouts) were identified. The mean density for each regeneration mode (N_r , total number of individuals with dbh < 5 cm per plot) was calculated for each site.

Demographic structure of tree stands

Diameter classes with a 5 cm interval were established for each study site. These classes were then used to generate histograms adjusted to a theoretical three-parameter Weibull distribution. The probability density function associated with the Weibull distribution is defined as follows:

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

where x is tree diameter, a is the location parameter, b is the scale parameter, and c is the shape parameter, which characterises the observed structure.

Spatial structure of tree stands

Geary's method, based on the spatial positioning of all recorded trees, was applied. This method provides results across multiple observation scales and detects local spatial autocorrelation, revealing fine-scale tree distribution patterns. A univariate analysis of tree distribution [function $G_{11}(r)$], was performed to assess the overall spatial arrangement (random, aggregated, or uniform). Additionally, a bivariate analysis [function $G_{12}(r)$] was conducted to evaluate the spatial relationship between young trees (5 cm $<$ dbh $<$ 25 cm) and adult trees (dbh $>$ 25 cm).

RESULTS

Resource abundance

The results are presented in Table 1. A significant difference in tree density was observed between the three sites ($P = 0.003$). In Kouassi-N'Dawa, tree density was recorded as 40.7 ± 10.5 trees ha^{-1} , in comparison to 22.3 ± 6.4 trees ha^{-1} in Koumokro, which itself was higher than in Pouniakele (6.3 ± 0.6 trees ha^{-1}). The coefficients of variation ranged from low to moderate (9–29%). Basal area was similar across the three sites ($P = 0.441$), with mean values of 0.8 ± 0.3 $\text{m}^2 \text{ha}^{-1}$ in Koumokro, 0.5 ± 0.3 $\text{m}^2 \text{ha}^{-1}$ in Kouassi-N'Dawa, and 0.5 ± 0.4 $\text{m}^2 \text{ha}^{-1}$ in Pouniakele. The coefficients of variation ranged between 38–80%.

Natural regeneration strategies

Two modes of natural regeneration were identified: natural seedling recruitment and stump sprouting (Table 2). The natural seedling density exhibited significant variation among sites ($P = 0.038$), while stump sprout density demonstrated no significant difference ($P = 0.131$). The highest natural seedling density was recorded in Kouassi-N'Dawa (47 seedlings ha^{-1}), followed by Koumokro (40 seedlings ha^{-1}), while Pouniakele exhibited a significantly lower density of 7 seedlings ha^{-1} . The coefficients of variation for natural seedling density ranged from 45–62%. For stump sprouting, the distribution was more heterogeneous, although no statistical difference was identified ($P = 0.131$). In Koumokro, the mean stump sprout density was recorded at 78 sprouts ha^{-1} , which was four times lower than in Kouassi-N'Dawa and ten times lower than in Pouniakele. The coefficients of variation were classified as high to very high (40–81%). Furthermore, within-site comparisons of the two regeneration modes revealed no significant differences in Kouassi-N'Dawa ($P = 0.15$), Koumokro ($P = 0.37$), and Pouniakele ($P = 0.63$).

Demographic structure of tree stands

The stand's data revealed 8, 13, and 21 diameter classes in Kouassi-N'Dawa, Koumokro, and Pouniakele, respectively. The horizontal structure (Figure 1) exhibited an inverted J-shaped distribution ($c < 1$) in the Kouassi-N'Dawa and Koumokro stands, indicating a predominance of young individuals (dbh = 5–10 cm). In these two sites, individuals with dbh between 5–20 cm accounted for 87% of the stand. Furthermore, individuals with dbh > 50 cm were nearly absent in Kouassi-N'Dawa.

The stand in Pouniakele exhibited a positively skewed distribution ($1 < c = 1.11 < 3.6$), with a predominance of small-diameter trees (5–15 cm) and intermediate-diameter trees (30–45 cm) (Figure 1).

Spatial distribution pattern of tree stands

Tree distribution by site

The analysis of tree spatial distribution (regardless of age class) revealed a consistent aggregated pattern across all three stands. The $G_{11}(r)$ function remained above the confidence envelope, indicating an aggregated spatial distribution at distance intervals of 67 m in Kouassi-N'Dawa, 75 m in Pouniakele, and 147 m in Koumokro. Beyond these distances, the function fell within the confidence envelope, suggesting a random spatial distribution of trees (Figure 2).

Spatial relationship between juvenile and adult trees

The spatial distribution of juvenile trees relative to adult trees exhibited variation across the three stands. In general, the curves remained above the confidence envelope in Koumokro and Pouniakele, suggesting an aggregated distribution of young trees around adult trees. However, in Kouassi-N'Dawa, the distribution pattern fluctuated between random and repulsive (Figure 3).

DISCUSSION

Resource availability

Two modes of natural regeneration were observed in *K. senegalensis*: natural seedling

Table 1 Mean values ($\pm$ standard deviations) of density and basal area parameters assessed in the *Khaya senegalensis* stands

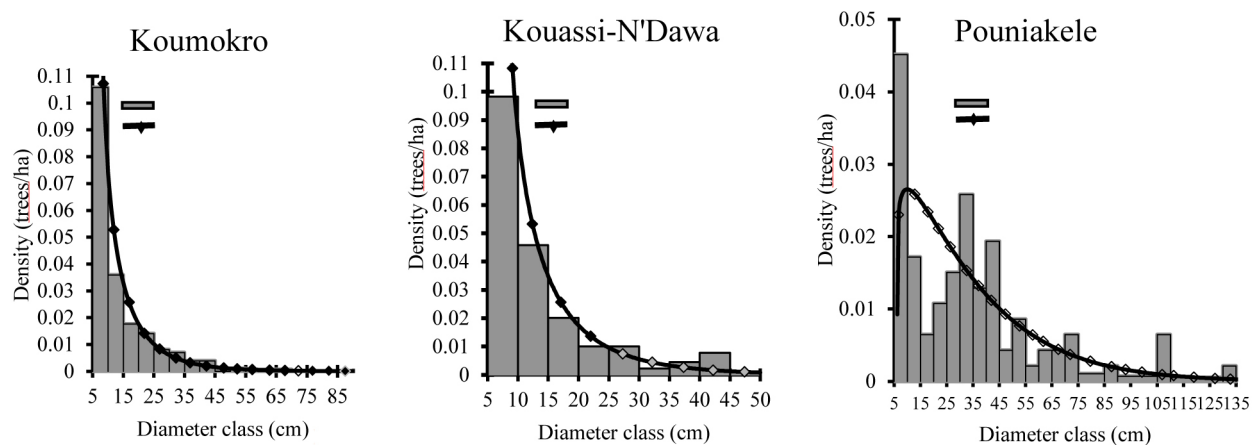
Parameters	Tree stands						Statistical tests	
	Kouassi-N'Dawa	CV	Koumokro	CV	Pouniakele	CV	<i>F</i>	<i>P</i>
Densities (trees ha^{-1})	40.7 $\pm$ 10.5 ^a	25.8	22.3 $\pm$ 6.4 ^b	28.7	6.3 $\pm$ 0.6 ^c	9.52	17.48	0.003
Basal area ($\text{m}^2 \text{ha}^{-1}$)	0.5 $\pm$ 0.3	60.0	0.8 $\pm$ 0.3	37.5	0.5 $\pm$ 0.4	80.0	0.94	0.441 ^{ns}

$P < 0.05$ = significant probability, ns = non-significant probability, CV = coefficient of variation in percentage (%)

Table 2 Mean values ($\pm$ standard deviations) of regeneration mode densities observed in the three study sites.

Regeneration modes	Regeneration density						Statistical tests	
	Kouassi-N'Dawa	CV	Koumokro	CV	Pouniakele	CV	<i>F</i>	<i>P</i>
Natural seedlings (seedlings ha ⁻¹)	47.0 $\pm$ 27.4 ^a	58.3	40.0 $\pm$ 18.3 ^{ab}	45.75	7.0 $\pm$ 4.4 ^b	62.86	9.2	0.038
Stump sprouts (sprouts ha ⁻¹)	17.7 $\pm$ 9.3	52.54	78.7 $\pm$ 63.8	81.07	8.7 $\pm$ 3.5	40.23	3.6	0.131
<i>t</i>	1.76		-1.01		-0.52			
<i>P</i>	0.15 ^{ns}		0.37 ^{ns}		0.63 ^{ns}			

$P < 0.05$ = significant probability, ns = non-significant probability, CV = coefficient of variation in percentage (%)

**Figure 1** Diameter class distribution of *Khaya senegalensis* trees in Kouassi-N'Dawa, Koumokro, and Pouniakele stands

recruitment and stump sprouting. In Kouassi-N'Dawa, natural seedling recruitment was the dominant mode (73%), while stump sprouting accounted for only 17%. In Koumokro, 34% of the regeneration came from seedlings, whereas stump sprouts contributed 66%. In Pouniakele, both regeneration modes were nearly equal, with 47% from seedlings and 53% from stump sprouts. These patterns reflect the different management practices and disturbances affecting the stands. Kouassi-N'Dawa, a sacred forest, benefits from strong natural resource protection (prohibition of bushfires, tree felling, and bark harvesting). Consequently, very few trees are cut down, leading to the low presence of stump sprouts. Despite the comparable seedling density in Koumokro and Kouassi-N'Dawa, the higher proportion of stump sprouting in Koumokro suggests greater degree

of human impact, likely resulting from extensive tree harvesting. The high stump sprout density observed in Koumokro is indicative of extensive tree cutting, while in Pouniakele, the very low overall regeneration rates (7 seedlings ha⁻¹ and 8 stump sprouts ha⁻¹) point to significant disturbances. Agricultural practices, including land clearing and post-harvest grazing, likely prevented seed germination and seedling establishment. These findings echo the work of Waya et al. (2022) on *Adansonia digitata* in the Pendjari Reserve, revealing comparable dynamics: a differential sensitivity of age classes to anthropogenic pressures, with significantly lower regeneration in disturbed areas (7.33 juveniles ha⁻¹ versus 35.33 in protected areas).

However, across all three sites, *K. senegalensis* demonstrated a strong ability to regenerate. This regeneration capacity presents a valuable

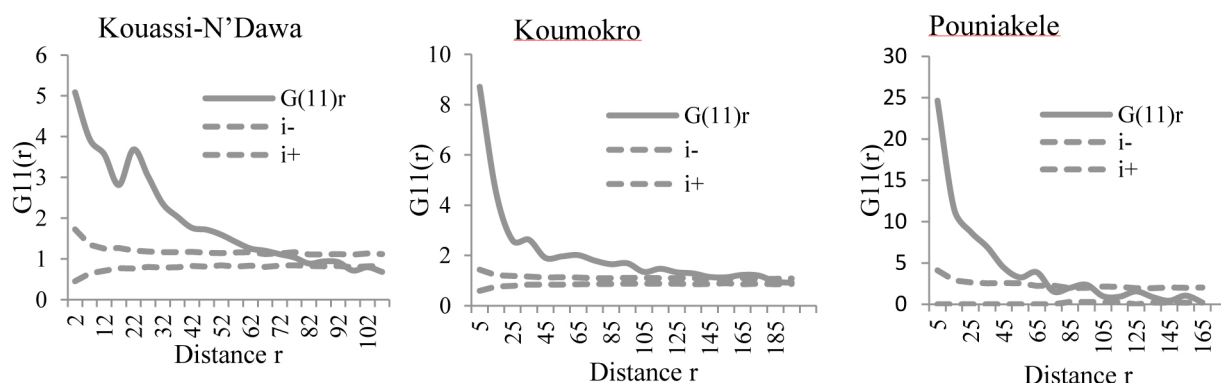


Figure 2 Spatial distribution of *Khaya senegalensis* trees in Kouassi-N'Dawa, Koumokro, and Pouniakele stands

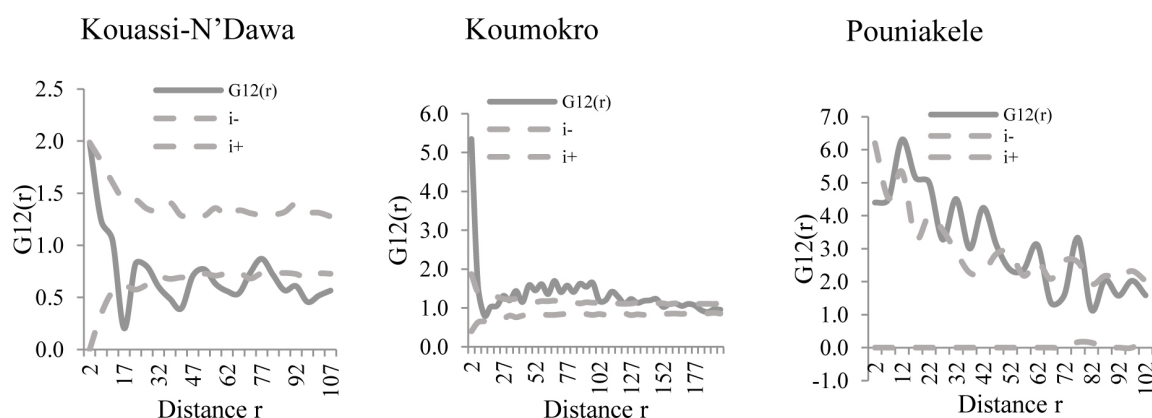


Figure 3 Bivariate spatial distribution between juvenile and adult *Khaya senegalensis* trees in Kouassi-N'Dawa, Koumokro, and Pouniakele stands

opportunity for nursery production and future plantations. Analogous to *Tectona grandis* (teak), which can regenerate through coppicing (Voui et al. 2012), *K. senegalensis* is a promising candidate for reforestation programs aimed at restoring degraded protected areas.

Anthropogenic pressures, such as agriculture, logging, and overgrazing, have a significant influence on the structure and dynamics of the studied stands. However, the impact of these pressures varies greatly from one site to another, depending on the human activities present. In Kouassi-N'Dawa, a sacred forest, the absence of significant anthropogenic pressures is a key factor in the high tree density observed (40.7 ± 10.5 trees ha^{-1}). As a protected area, access and exploitation are prohibited, allowing the vegetation to grow without disturbance. This results in a relatively higher tree density and sustained natural regeneration, contributing to the stability of the stand. This area thus represents an example of how the absence of human disturbance promotes the conservation

and growth of forest stands. In Koumokro, although the tree density (22.3 ± 6.4 trees ha^{-1}) is still relatively higher than in Pouniakele (6.3 ± 0.6 trees ha^{-1}), anthropogenic pressures such as agriculture and logging for charcoal production have notable effects. These practices limit the space available for young trees, disrupt natural regeneration, and fragment the forest habitat. As a result, although the site is still relatively well-covered, more intensive forest management will reduce diversity and affect stand dynamics in the long term. Finally, in Pouniakele, a site heavily affected by intensive agriculture, overgrazing, and wood cutting, the tree density is particularly low (6.3 ± 0.6 trees ha^{-1}). Human activities such as land clearing for agriculture and pruning of trees for livestock feed have led to a significant loss of forest cover. These pressures limit natural regeneration, fragment habitats, and make it difficult to maintain tree diversity within the stand. These results align with those observed by Guinde et al. (2023) on *Vitex doniana* in Burkina Faso, which showed that intensely

exploited agricultural areas not only have very low densities (5.44 ± 2.80 trees ha^{-1}) but also significantly compromised regeneration. Conversely, protected areas offer a more favorable environment for natural regeneration, with more balanced stand structures.

Nonetheless, the overall tree density (23 trees ha^{-1}) observed in this study is significantly higher than that reported for *Pterocarpus erinaceus* (9 trees ha^{-1} ; Goba et al. 2019) and *K. senegalensis* (6 trees ha^{-1} ; Houphouet et al. 2023) in Ivorian savannas. Depending on the level of ecosystem exploitation, disturbances may be more pronounced. This phenomenon is evident in Koumokro, where human activities are less intense than in Pouniakele, resulting in a tree density that is lower than Kouassi-N'Dawa but still higher than Pouniakele.

Demographic structure

The diameter class distribution of trees in each site followed different theoretical Weibull distributions ($P > 0.05$). In Kouassi-N'Dawa ($c = 0.77$) and Koumokro ($c = 0.92$), the shape parameter c was less than 1, indicating an inverted J-shaped distribution. This distribution is characteristic of forest ecosystems that have experienced minimal disturbance, such as the sacred forest in Kouassi-N'Dawa, where stringent protection measures against logging ensure regular natural regeneration and balanced diameter class distributions. This location serves as a reference point, providing a basis for understanding the impacts of human activity on tree stands in other regions. According to Chazdon & Guariguata (2016), protected forests tend to exhibit diameter structures favouring an abundance of young and intermediate-sized trees due to intra- and interspecific competition. The similar structure observed in Koumokro suggests that local land use practices do not severely disrupt *K. senegalensis* stands. Despite not being designated as a sacred forest, Koumokro experiences reduced human pressures relative to Pouniakele, characterised by minimal grazing, limited agriculture, and infrequent charcoal harvesting. The observed balanced regeneration in Koumokro might be indicative of a more stable tree diameter class distribution. However, the absence of large seed-bearing trees ($\text{dbh} > 90$ cm) could be attributed to selective logging

for charcoal and other socio-economic activities.

In contrast, the Pouniakele stand ($c = 1.11$) exhibited a positively skewed distribution, with the majority of trees falling within the 25–55 cm dbh range (43.01%). This pattern, where $1 \leq c \leq 3.6$, indicates a negatively skewed or right-skewed distribution, which could result from intense anthropogenic and zoo-anthropogenic pressures (grazing, tree topping, crown pruning, harmful pollarding, wood harvesting for mortar and pestle production, and bark stripping for medicinal use). These activities create erratic peaks in tree size distribution (Lasky et al. 2014). These results corroborate those of Chakocha et al. (2025) in their study on *Canarium schweinfurthii* in Cameroon, where the diametric structure of stands in highly disturbed areas (both forest and savanna zones) presented an irregular “sawtooth” profile.

Spatial distribution pattern

The overall spatial arrangement of trees in the three stands revealed a short-distance aggregated distribution, with aggregation observed at 62 m in Kouassi-N'Dawa, 125 m in Koumokro, and 75 m in Pouniakele. These variations in aggregation distance may be influenced by seed dispersal limitations, with denser and more closed-canopy sites (e.g., Kouassi-N'Dawa) exhibiting shorter aggregation distances, whereas more open and less densely forested sites (e.g., Koumokro) showing longer aggregation distances. At intermediate scales, secondary dispersal and competition modify this structure, while at larger scales, tree arrangement becomes stochastic (Pélissier et al. 2010).

The spatial distribution of juvenile trees relative to adult trees showed aggregated patterns in Koumokro and Pouniakele. This aggregation is likely due to limited seed dispersal, primarily by gravity (barochory), leading to clustered seedlings around parent trees. Jiang et al. (2018) reported that barochory is a common dispersal mechanism among savanna species. Additionally, *K. senegalensis*, like many large savanna trees, provides shade that facilitates seedling establishment (Azihou et al. 2013). In contrast, the spatial distribution in Kouassi-N'Dawa was more random at short distances and became increasingly repulsive as distance increased. This pattern may be attributed to the

site's topography and edaphic conditions, which likely influence seed dispersal and seedling establishment. Steep slopes, shallow soils, or rocky terrain may have limited the recruitment of juveniles near seed-bearing trees (Shi Hang et al. 2019).

CONCLUSION

This study highlighted the structural parameters of *K. senegalensis* across three stands with contrasting management practices. Our results reveal diverse dendrometric, structural, and spatial characteristics. In sacred forests, which are less exposed to human pressures, tree and regeneration densities are higher. Conversely, highly disturbed areas show a structure dominated by stump sprouts and a scarcity of young seedlings. Less degraded sites are characterised by a predominance of small diameter classes. The observed regeneration modes include natural seedlings and stump sprouts. Seedlings dominate in stable sites, while sprouts indicate a response to felling. The spatial distribution of trees follows a clumped pattern, with varying distances depending on the site. Thus, the recommendations for sustainable management are as follows: (1) strengthen the legal and community protection of sacred forests, (2) combat illegal logging through participatory monitoring, and (3) train and educate local population on agricultural practices compatible with conservation.

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