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Characterization of stands and evaluation of carbon sequestration capacity of shea parklands (*Vitellaria paradoxa* C. F. Gaertn., Sapotaceae) in the departments of Dabakala and Kong, Ivory Coast

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ABSTRACT

This study aimed to characterize shea tree stands and assess the contribution of shea parklands to carbon sequestration in the Dabakala (north-central) and Kong (northeast) areas of Ivory Coast. It focused on 182 and 211 shea trees identified in each of these two areas, respectively. The diameter at 1.30 m above ground, the total height, and the basal area of the shea trees were measured. The spatial distribution pattern and aboveground biomass were calculated. Carbon and carbon dioxide equivalent (CO_2) stocks were also assessed. The results revealed higher dendrometric parameter values in Kong than in Dabakala. The average values of densities, basal areas, diameters and heights were 15.52 and 57.18 individuals.ha^{-1}; 1.16 ± 0.00 and 5.30 ± 0.02 m^2. ha^{-1}; 0.29 ± 0.10 and 0.33 ± 0.10 m and 8.90 ± 1.82 and 9.97 ± 1.53 m, respectively, at Dabakala and Kong. At Dabakala, the stored carbon and sequestered CO_2 equivalent were 0.66 ± 0.00 tC/ha and 2.42 ± 0.01 tCO_2/ha, compared to 3.17 ± 0.01 tC/ha and 11.63 ± 0.02 tCO_2/ha at Kong. However, the parks were characterized by the same aggregate distribution. Furthermore, the carbon sequestration potential varies along the phytogeographic gradient, from the centre to the north of the country. The knowledge gained from studies on these parks justifies strengthening the woody potential of ecosystems through planting or the practice of agroforestrys.

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INTRODUCTION

Shea, or *Vitellaria paradoxa* C. F. Gaertn., is a Sapotaceae endemic to Africa. It grows wild in the Sudanian savannas of the sub-Saharan Sahara. Shea trees cover a geographical band extending from eastern Senegal to northwestern Uganda (Diarrassouba *et al.*, 2007). This band, approximately 5,000 km long, is located between the 16th and 34th parallels of longitude. *V. paradoxa* plays an important socio-economic, ecological, cultural, and agricultural role for rural populations. It is a multi-purpose tree in African communities. The sale of shea nuts and butter provides significant income for women in the North (Diarrassouba *et al.*, 2008).

Given the global concern of mitigating climate change (CC) due to greenhouse gas (GHG) emissions, particularly carbon, woody vegetation is expected to play a major role in CC adaptation through carbon sequestration. This woody biomass is an important indicator for understanding the functioning, ecological productivity, and economic performance of agroecosystems. Its study allows us to grasp the contribution of agricultural systems to the local economy and the environment (Bonde, 2019). Furthermore, it provides information on the quantity of organic matter produced, which allows us to assess the health and productive capacity of these systems. Furthermore, woody biomass can be used to assess carbon sequestration potential, thus contributing to the fight against climate change (Breman and Kessler, 1995; Kémeuzé *et al.*, 2012). Work by Dimobe and Bayala (2023) showed that shea agroforestry parklands contribute significantly to carbon sequestration and that the extent of these benefits varies with the diameter at breast height (DBH) of the trees and the phytogeographical areas. The carbon sequestration capacity of trees increases with age, making them carbon reservoirs. Similarly, Alui *et al.* (2020) observed that the spatial distribution of shea trees depends on soil type. They also reported that the sequestered CO2 equivalents, primarily found in shrubby savannas, contribute to limiting greenhouse gas emissions into the atmosphere. In Ivory Coast, data on the biomass produced by the shea tree, whose geographic range extends from the center to the north of the country (Diarrassouba *et al.*, 2008), are less abundant. However, knowledge of this biomass would improve the management of the species in agroecosystems and could thus contribute to the resilience of rural populations in the face of changing climate variables. It is therefore reasonable to estimate and assess its carbon sequestration capacity under the influence of the various agroecological conditions related to its distribution area in the context of climate change.

It is with this in mind that the present study was undertaken to guide stakeholders in the shea sector towards new approaches to its exploitation. Its objective is to characterize the stands and assess the contribution of shea parklands to carbon sequestration in the Dabakala (north-central) and Kong (northeast) areas of Ivory Coast. Specifically, it aims to: (i) determine the dendrometric structure and spatial distribution of shea stands in the study areas and (ii) estimate the total biomass and carbon stock of the studied shea parklands.

MATERIALS AND METHODS

Study sites

The work was carried out in two shea parks in Ivory Coast: one in Boniérédougou and the other in Sikolo, located in the departments of Dabakala and Kong, respectively. Boniérédougou, with geographic coordinates of 8°23’ North latitude and 4°44’ West longitude, is situated in the east-central part of the Hambol region (Fig. 1). It lies within the sub-Sudanian savanna, with a bimodal Sudano-Guinean climate: a rainy season lasting seven months and a shorter dry season of five months. The average monthly temperature is 28.20 °C (Fig. 2) (Climate Data, 2022 a). The soils are of ferrallitic types dominated by clayey-sandy (shallow soil) and gravelly soils (Soro *et al.*, 2011). Hydromorphic soils are also found in the low-lying and marshy areas. The vegetation is that of pre-forest savannas. For the most part, it belongs to the sub-Sudanese sector of the Sudanian zone (Soro *et al.*, 2011). The locality of Sikolo, located between 9°27’ North latitude and 4°43’ West longitude, is in northeastern of Ivory Coast (Fig. 3). It is situated in the Tchologo region.

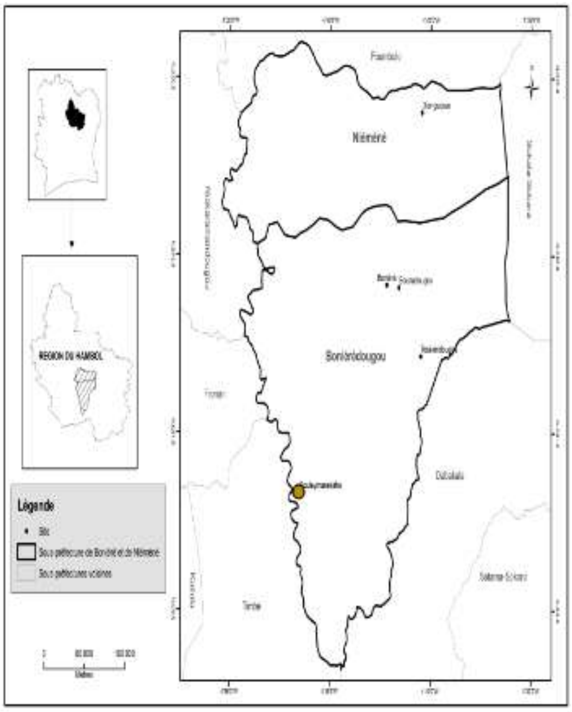

Fig. 1. Location of the shea park in Boniérédougou (Dabakala)

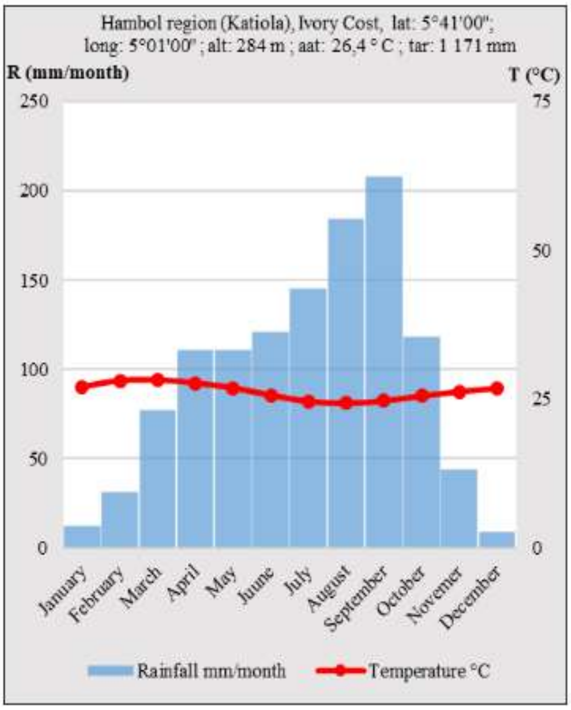

Fig. 2. Ombrothermal curve of the Hambol region from 1991 to 2021

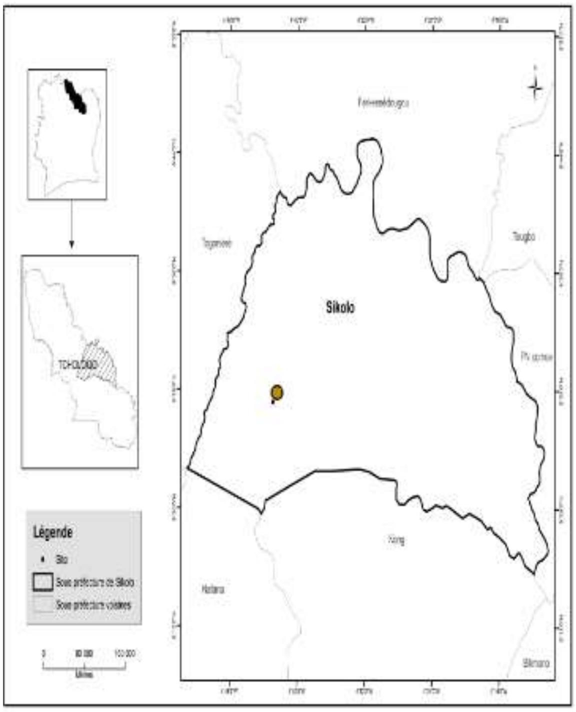

Fig. 3. Location of the Sikolo shea park (Kong)

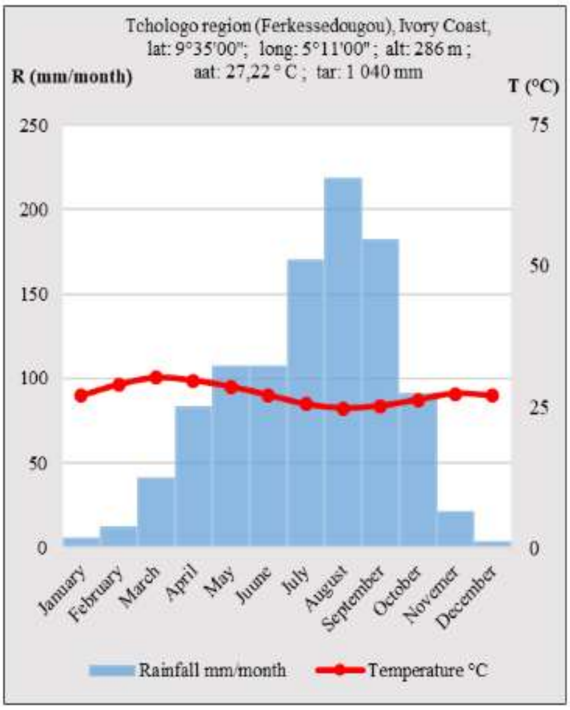

Fig. 4. Ombrothermal curve of the Tchologo region from 1991 to 2021

The climate is of the Sudanian type, with a dry season lasting seven months and a short rainy season extending over five months. The average monthly temperature is 30.10 °C (Fig. 4) (Climate Data, 2022 b). The soils are generally sandy, gravelly, or lateritic. The criteria for selecting these parks are the low anthropogenic pressure (bushfires, debarking, and pruning) they experience and their location within the "shea belt" of West Africa. The average density varies between 15 and 57 trees per hectare in the shea parks.

Plant material

The plant material consisted of shea trees identified in two agroforestry parks. Only trees with a circumference greater than 16 cm were selected for the study. Stems with a circumference of less than 16 cm and/or shea stems with a size of less than one (1) meter are classified among the potential regenerations (Kabore, 2010; Thiombiano *et al.*, 2016).

Technical equipment

The technical equipment consisted of an etrex 30 GPS receiver, a tape measure, a SUUINTO clinometer, two wooden ladders, paint pots, two brushes, labels and field data collection sheets.

Data collection

The areas of these shea parks were measured using a GPS receiver, along with the geographic coordinates of the shea trees within them. Maps of the two agroforestry shea parks were created. The number of shea trees was counted. Dendrometric measurements were taken in each park. The measurements focused on shea trees with a basal circumference greater than or equal to 16 cm. For each individual tree, measurements included the circumference at 1.30 m above ground level and the total height. The characteristics of the shea parks include park mapping, the number of trees, spatial distribution, park density, basal area, and tree dendrometric structures.

Evaluation of dendrometric parameters

Density of shea parks

Density is defined as the number of individuals per unit area (Minda *et al.*, 2013). The method consisted of counting the shea trees and then dividing this number by the park area (Dotchamou *et al.*, 2016). The actual density was calculated for each site using the following equation:

$$N = (1000 \times n) / S$$

N: number of trees per hectare (density); n: number of stems with a diameter of 1.3 m ≥ 5 cm; S: the total area in m² or ha. It was determined using GPS. Trees with a diameter of 1.3 m < 5 cm were not included in this study.

Basal area of shea parklands

According to Rondeux (1993), basal area, expressed in m²/ha, is the cross-sectional area of the trunks of all trees in a survey at 1.30 m above ground level. It corresponds to the sum of the basal areas of all shea trees, the results of which have been converted to a per-hectare ratio. This parameter better reflects the horizontal land cover of plant species and is characteristic of the stability of a biotope (Rollet, 1974). The trunk circumferences of all shea trees populating each of the shea parklands were measured using a tape measure. The basal area was then determined from the sum of the areas of the individual cross-sections of all the trees in the park, divided by the area of the agroecosystem, according to the following formulas (Ndiaye *et al.*, 2014):

$$g_i = C_i^2 / 4\pi$$

g_i: basal area of an individual in m²; C_i: circumference of individual i in m;

π= 3.14 (the stem cross-sections being approximated as cylinders).

$$G = \frac{1}{S} \times \sum_{i=1}^{n} C_i^2 / 4\pi$$

G: basal area expressed in m2.ha-1; C: circumference at 1.30 m from the ground expressed in m; S: area of the Shea Park expressed in ha.

Assessment of the structure of shea trees in the parks

Horizontal structure

The horizontal structure, or trunk diameter, allows for the assessment of the relative diameters of individual trees within a stand. The circumference of the trees in the shea parks was measured using a tape measure at 1.30 m above the ground. The diameters were then determined using the following formula.

$$D = C_i / \pi$$

D: trunk diameter in meters; C_i: circumference of tree $_i$ in meters; π = 3.14.

The distribution of individuals by diameter class, called "total structure" (Bouko *et al.*, 2007), allows us to understand the demographic structure of the woody stands. The range of the distribution was 0.1 m.

Vertical structure

The vertical structure, or total height of the trees in the parks, reflects the layering of the individual trees from the ground to the canopy. Heights were determined using a "SUUNTO" clinometer. The range of the distribution was 2 m.

Determining the spatial distribution of shea trees in parks

The distribution index allows us to determine the spatial structure of the trees in the parks. The quadrat method of Canard and Poinsot (2004) was used for this purpose. It consisted of covering the studied shea parks with K grid squares of regular shapes. The trees considered are represented as points after georeferencing using ArcGIS software. The average number of points per grid square is equal to D = N/K. Each grid square i was associated with a number Di of points it contains. Then, the variance (VD) was calculated to deduce the Distribution Index (RI), the formula for which is as follows:

$$RI = VD / D$$

RI: Distribution Index; VD: Variance; D: Mean; N: Number of trees; K: Number of grid squares.

The values obtained are interpreted as follows:

RI ≈ 1: random distribution (Poisson distribution);

RI > 1: a rather aggregated distribution;

RI < 1: a rather regular distribution.

Assessment of the total biomass of shea trees in the parks

Biomass values were calculated using the height and diameter data of each individual tree, and certain formulas validated by the Intergovernmental Panel on Climate Change (IPCC, 2006 and 2007). Total biomass includes aboveground biomass and belowground or root biomass.

Assessment of aboveground biomass

Aboveground biomass (AGB) corresponds to the mass of dry plant matter per unit area. It can be calculated using allometric models or strong wood volume models. However, strong wood volume models were chosen because this less destructive method takes into account tree parameters such as diameter, specific gravity, and total height. It consists of recording the diameter (d1.3m) and the total height of all the shea trees surveyed, as described above. Aboveground biomass is thus calculated using the following expression (Chave *et al.,* 2005):

$$AGB = \exp[-2{,}187+0{,}916 \ln(\rho H D^2)]$$

D: diameter at human chest height (MBH) expressed in meters; ρ: specific density of wood expressed in t/m^3 dried at 103°C; H: total height of the tree expressed in meters and AGB in tons. Ln: natural logarithm. For species whose specific density is not known, the average density ρ = 0.58 t/m^3 is assigned.

Belowground biomass

The belowground or root biomass (BGB) of standing shea stands was assessed using the IPCC method (2006). Thus, the belowground biomass (BGB) of each tree is assessed from the aboveground biomass according to the model eveloped by Cairns *and al.* (1997):

$$BGB = \exp[-1{,}0587 + 0{,}8836 \times \ln(AGB)]$$

BGB: Belowground biomass expressed in tons; AGB: Aboveground biomass expressed in tons; Ln: natural logarithm.

Total biomass

The total biomass of each tree (TB) is the sum of its aboveground biomass and its belowground biomass: TB= AGB + BGB

$$TB = \exp[-2{,}187+0{,}916 \ln(\rho H D^2)] + \exp[-1{,}0587 + 0{,}8836 \times \ln(AGB)]$$

TB: Total biomass expressed in tDM.ha^{-1}. Biomass is obtained per site by adding the biomass of all individual trees surveyed, followed by extrapolation to the hectare level.

Estimation of carbon stock and carbon dioxide equivalent

The carbon stock of the parks was calculated from biomass data (IPCC, 2003 and 2006).

Carbon stock assessment

Carbon stock is assessed by assigning a coefficient, called the carbon ratio or carbon fraction (CF), to the total biomass. This coefficient ranges from 0.47 to 0.5. However, the value of 0.47 was chosen in accordance with the IPCC recommendations (2003). Carbon Stock (CS) is calculated using the formula (Folega *et al.*, 2020):

$$CS = TB \times CF \text{ ou } CS = TB \times 0{,}47$$

CS: Carbon stock stored in total biomass expressed in $tC.ha^{-1}$, TB: Total biomass expressed in $tMS.ha^{-1}$, and CF: Deficiency carbon fraction of all species combined expressed as a percentage (%), and is equal to 0.47.

Estimation of the equivalent atmospheric CO_2 stock

Considering the molar mass of each of the CO_2 components, the carbon (C) to oxygen (O_2) combination ratio is 3.67. The equivalent atmospheric CO_2 stock is estimated by multiplying the carbon stock from biomass by 3.67, according to the method of Tsoumou *et al.* (2016). The equivalent atmospheric CO_2 from shea parklands was thus determined using the formula:

$$tCO_{2eq} = SC \times 3{,}67$$

CO_2eq: Sequestered atmospheric carbon dioxide stock expressed in t $CO2.ha^{-1}$; 3.67: Carbon (C) to oxygen (O_2) combination ratio; CS: Carbon stock expressed in $tC.ha^{-1}$

Data processing and analysis

Excel 2007 was used for data entry and processing. ArcGIS and Excel 2007 were used to map the parks. RCMDR version 2.9-5 (R.4.3.1) was used for statistical analysis of the parameters recorded on the trees of the studied shea populations. It also served as the basis for the various statistical tests. The significance level chosen for these analyses was 5% ($\alpha = 0.05$). The Kolmogorov-Smirnov normality test on the population distribution and Levene's test on the equality of variances were used. Student's t-test and Welch's t-test for independent samples were also used to compare the mean parameters of the populations from the two sites. Diameter at breast height (DBH) and total tree height were sorted by class and used to construct histograms using Excel 2007 spreadsheet.

RESULTS

Dendrometric parameters and park areas

The dendrometric characteristics of the shea trees and the park areas are presented in Table 1.

Table 1. Dendrometric characteristics of shea trees and area of the parks

Sites	Number of trees	Area (ha)	Basal area ($m^2.ha^{-1}$)	Density (individu.ha^{-1})	Trunk diameter (m)	Total height (m)
Boniérédougou	182	11.73	1.16 ± 0.00^b	15.52^b	0.29 ± 0.10^b	8.90 ± 1.82^b
Sikolo	211	3.69	5.30 ± 0.02^a	57.18^a	0.33 ± 0.10^a	9.97 ± 1.53^a
p-value			0.0001	0.0001	0.0001	0.0001
α			0.05	0.05	0.05	0.05

Number of shea trees, areas and densities of the shea parks studied

The number of trees with a diameter of 1.30 m greater than or equal to 5 cm recorded in the Boniérédougou and Sikolo parks was 182 and 211, respectively. The measured areas were 11.73 ha for the Boniérédougou park and 3.69 ha for the Sikolo park. The density of the Sikolo park was 57.18 individuals/ha, which is five times greater than that of the Boniérédougou site (15.52 individuals/ha) (Table 1).

Basal area of the parks

The basal areas obtained at Boniérédougou and Sikolo were 1.16 ± 0.00 $m^2.ha^{-1}$ and 5.30 ± 0.02 $m^2.ha^{-1}$, respectively. The basal area of the shea trees was higher at the Sikolo site (5.30 $m^2.ha^{-1}$) compared to that of Boniérédougou (1.16 ± 0.00 $m^2.ha^{-1}$) (Table 1).

Stand structure in shea parks

Horizontal structure

The overall distribution of trunk diameter classes in the shea parks of Boniérédougou and Sikolo closely resembled a normal curve (Fig. 5). These structures were characteristic of stands with low natural regeneration potential, as they exhibited small quantities of trees with both small and very large diameters. However, in the Boniérédougou site, the majority of trees were found in the three lowest classes, ranging from 0.1 to 0.4 m. In the Sikolo park, most trees were found in the intermediate classes, between 0.2 and 0.4 m (Fig. 5).

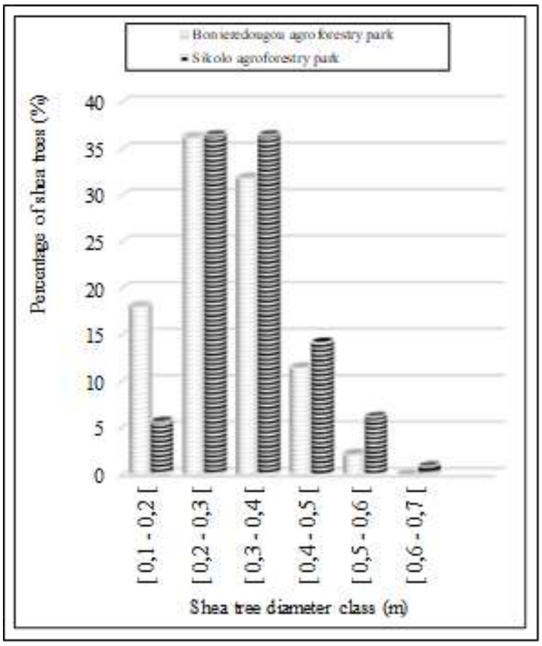

Fig. 5. Percentages of trees according to the diametric structure and the classes defined

Shea trees with large trunks were more frequent in Sikolo National Park than in Boniérédougou National Park (Fig. 5). The diameters of shea trees in the two study areas were significantly different (t = -3.523, df = 391, $p \leq 0.05$) (Table 1). In both parks, the percentages of shea trees belonging to the diameter classes [0.2–0.4] were the highest (31% to 36%). However, for the [0.2–0.3] class, the percentages of shea trees in Boniérédougou National Park (36.3%) and Sikolo National Park (36.5%) were almost identical. As for the [0.3–0.4] class, Sikolo National Park had the highest average value (36% versus 31%). Regarding the first class [0.1–0.2 m], the percentage of shea trees in Boniérédougou Park (18.13%) was higher than that in Sikolo Park (5.70%). With diameter classes between 0.4 and 0.6 m or more, the percentages of shea trees in both parks gradually decreased.

Vertical structure

The height distribution of shea trees in Boniérédougou closely follows a normal curve (Fig. 6). The majority of trees (89.6% in Boniérédougou and 94.8% in Sikolo) were found in the three height classes between 6 and 12 m. The distribution of trees within the Sikolo Agroforestry Park can be broadly described as bell-shaped (Fig. 6). Shea trees with greater heights are more prevalent (94.8%) in Sikolo than in Boniérédougou (89.6%) (Fig. 6). The proportion of large shea trees in Sikolo spans the 8–12 m class, while in Boniérédougou it spans the 6–12 m class. For class [8 – 10[, the percentages of trees were roughly equivalent on both sites (37.4% in Boniérédougou and 36.5% in Sikolo). However, for the [10–12] class, the Sikolo site had the highest rate (49.3%) compared to Boniérédougou (24.7%). The percentage of trees in the [6–12] class in Boniérédougou was higher (27.5%) than in Sikolo (9.00%). For the total height class below 4 m, the trees in both study areas had the same percentage (0.5%). The [4–6] class in Boniérédougou had a higher proportion (5.5%) than in Sikolo (0.9%). As for the total height classes of 12 m and above, the percentages were the same and gradually decreased from 3.80% to 0.5%. The shea parkland at Boniérédougou was dominated by individuals in the [6–10[class, representing 64.90%; while that at Sikolo was composed of 85.80% individuals with a total height between 8 and 10 m (Fig. 6). It is clear that the largest shea trees were identified in the Tchologo region (Sikolo) (Table 1).

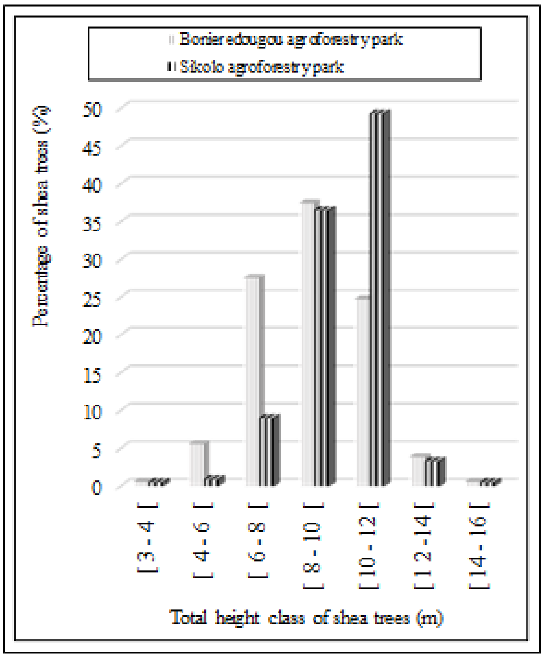

Fig. 6. Percentages of trees according to the vertical structure and the classes defined

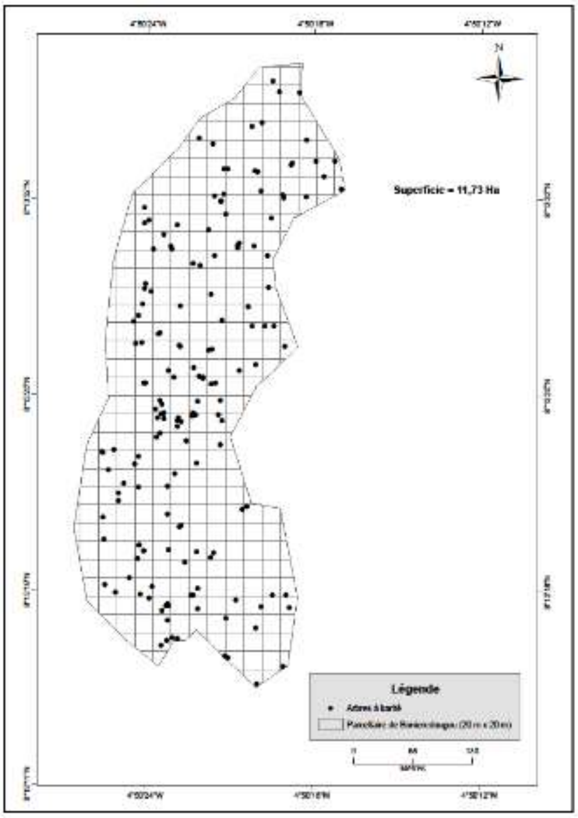

Fig. 7. Spatial distribution of shea trees in the Boniérédougou agroforestry park

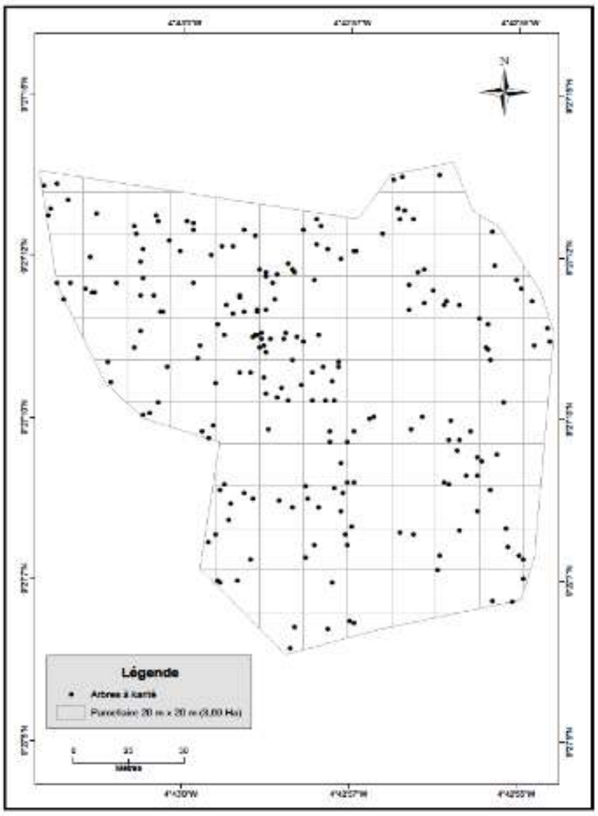

Fig. 8. Spatial distribution of shea trees in the Sikolo agroforestry park

Table 2. Distribution index of shea trees in agroforestery parks

Sites	Average number of stems par quadrat (AG)	Variance (VD)	Distribution index (DI)	Distribution type
Bonieredougou	0.45	0.97	2.18	Agrégatif
Sikolo	2.36	5.12	2.17	Agrégatif

Table 3. Biomass and carbon stock of shea parks

Site	Aboveground biomass (t DM.ha^{-1})	Underground biomass (t DM.ha^{-1})	Total biomass (t DM.ha^{-1})	Carbon stock (t C.ha^{-1})	Equivalent CO_2 stock (t CO_2.ha^{-1})
Bonieredougou	0.95 ± 0.00^b	0.45 ± 0.00^b	1.40 ± 0.00^b	0.66 ± 0.00^b	2.42 ± 0.01^b
Sikolo	4.62 ± 0.01^a	2.11 ± 0.01^a	6.74 ± 0.02^a	3.17 ± 0.01^a	11.63 ± 0.02^a
p-value	0.0001	0.0001	0.0001	0.0001	0.0001
α	0.05	0.05	0.05	0.05	0.05

Spatial distribution of shea trees in agroforestry parks

The spatial distributions of shea trees in the two agroforestry parks studied are shown in Fig. 7 and 8. They revealed a similar arrangement of shea trees across the field. Furthermore, the distribution indices (RI) of the trees in the two parks were practically identical (2.18 for Boniérédougou and 2.17 for Sikolo). The spatial distributions of the woody plants were also of an aggregate type (Table 2).

Biomass and carbon stock

Aboveground biomass (AGB), belowground biomass (BGB), total biomass (TB), and the quantities of stored carbon and CO_2 equivalent are presented in Table 3. The t-test showed significant differences ($p \leq 0.05$) between the values of these parameters assessed in the two study areas. In Sikolo, the biomass and carbon stock values were higher than those in Boniérédougou. Specifically, aboveground and belowground biomass were 4.62 ± 0.01 t MS.ha^{-1}

and 2.11 ± 0.01 t $MS.ha^{-1}$ in Sikolo, compared to 0.95 ± 0.00 t $MS.ha^{-1}$ and 0.45 ± 0.00 t $MS.ha^{-1}$ in Boniérédougou. Total biomass and carbon stock were 6.74 ± 0.02 t MS.ha-1 and 3.17 ± 0.01 t C.ha-1 (Sikolo) and 1.40 ± 0.00 t MS.ha-1 and 0.66 ± 0.00 t C.ha-1 (Boniérédougou), respectively. Recorded CO_2 stock was 11.63 t CO_2.ha-1 in Sikolo and 2.42 ± 0.01 t CO_2.ha-1 in Boniérédougou (Table 3).

DISCUSSION

Average shea tree stand densities ranged from 15.52 to 57.18 trees per hectare. These figures are higher than those reported by Aleza *et al.* (2015) and Ouoba *et al.* (2023), who found densities ranging from 12 to 44 trees per hectare in Benin and from 8 to 45 trees per hectare in Burkina Faso. However, these values are lower than those obtained by Koura *et al.* (2013), with 39 to 70 trees per hectare in the agroforestry zones of Donga, in northwestern Benin. Our results thus show that shea (Vitellaria paradoxa) thrives in these regions of Tchologo and Hambol, which belong respectively to the Sudanian savanna and sub-Sudanese savanna phytogeographical sectors. Indeed, Diarrassouba *et al.* (2009) showed that shea parklands become denser along a south-north gradient, between the southern boundary passing between Katiola and Bouaké and the northern borders of Ivory Coast. However, the work of Thiombiano *et al.* (2016) and Bondé (2019) showed that average shea densities increase with the climatic gradient, from north to south in the agroforestry parklands of Burkina Faso (Ouoba *et al.*, 2023). Observations from these studies indicate that shea density is higher in the Sudanian zone of Ivory Coast. Furthermore, the work of Louppe (1995) showed that in savanna landscapes, the preferred habitat of Vitellaria paradoxa is the Sudanese savanna, where its density is highest. This density is similar to that of the southern Sudanese sector of Burkina Faso. The fact that the two sectors, namely the Sudanese sector of Ivory Coast and the southern Sudanese sector of Burkina Faso, are adjacent and share the same climate (Fontes and Guinko, 1995), explains the high density of this Sudanese phytogeographic zone. The results of this study reveal that several factors, including soil type, water, and light, influence the development of the shea tree. Indeed, it has been observed that climatic elements such as rainfall and temperature are very high. In Dabakala (Sudanian-Guinean savanna), rainfall lasts for seven months, with a higher amount than in Kong (Sudanian savanna) throughout the year, except for the month of August. In Kong, it is the high temperature (24.70 °C to 30.10 °C) that persists for seven months, with heat exceeding that of Dabakala year-round (Climate Data, 2022 a and b). Regarding the soils, they are usually shallow, loose, clay-ferrallitic and clay-sandy, and more or less fertile in places in Boniérédougou, and typically sandy, gravelly, or hardened in Sikolo (Soro *et al.*, 2011). These observations also agree with those of Nouvellet *et al.* (2006) who believe that the shea tree thrives in dry, sandy-clay soils with sufficient humus and can also adapt to lateritic soils. The low density of shea trees in Boniérédougou is thought to be linked to the high proportion of clay, which retains water, creating consistently damp areas unfavorable to shea tree growth. The sandy, gravelly, or lateritic soil of Sikolo, which allows for water infiltration and runoff, dries out very quickly, thus enabling the healthy development of shea trees and, naturally, a significant number of trees per unit area.

Regarding the basal area of shea trees, it was greater in Sikolo than in Boniérédougou. Indeed, the shea portion in the Kong area (Sikolo) contains more large-diameter trees than that of Dabakala (Boniérédougou). This value of 5.30 ± 0.02 $m^2.ha^{-1}$, obtained in Sikolo, is higher than those observed in the fields (2.63 ± 0.55 $m^2.ha^{-1}$) and fallow land (2.41 ± 0.34 $m^2.ha^{-1}$) of agroforestry parks in Burkina Faso (Ouoba *et al.*, 2023). Similarly, the basal area (5.30 m^2/ha) of the Sudanian zone in this study was greater than those of the 11 sites in the Sudanian and Sudano-Guinean zones of Benin, recorded (between 2.75 and 5.27 m^2/ha) by Dotchamou *et al.* (2016). It is clear that the higher number of shea trees per unit area in Kong is the main factor explaining the difference with the Sudanian zone of Ivory Coast and those of Burkina Faso and Benin. However, the basal areas obtained during the study were small compared to the findings obtained in the Sudanian zone of Benin by Fonton *et al.* (2012). The type of vegetation formation seems to explain this. Indeed, in the present study, only shea trees were considered, whereas the work of Fonton *et al.* (2012) covered all tree species with a diameter of 1.30 m > 5 cm.

The distribution of shea trees in the two agroforestry parks of Boniérédougou and Sikolo was almost identical, exhibiting an aggregated distribution.

The distribution indices obtained, 2.18 and 2.17 respectively, are similar to those obtained by some authors (Djossa *et al.* 2008; Fonton *et al.,* 2012). Indeed, *V. paradoxa* is a sarcochorous plant whose fully fleshy diaspores are released directly at the base of the seed-bearing trees. This results in a high concentration of seeds at the base of adult trees and, consequently, a significant number of plants of this species (Dotchamou *et al.*, 2012). The edible and attractive flesh attracts animals, which then disperse the seeds by eating and regurgitating them. Aggregated distribution is the rule in the plant kingdom, as indehiscent fruits like those of shea only fall below the canopy. There is therefore a low dispersion of the fruits compared to the parent trees. So much so that the study revealed that the positions of juvenile shea trees located outside the leafy crown are due to rodents, birds and bats (zoochory), and even humans. In the two shea parks of Boniérédougou and Sikolo, V. paradoxa individuals exhibit an aggregated spatial distribution, with clusters of varying sizes, depending on whether the fruit is sarcochorous or zoochorous. The studied aggregated distribution could also be explained by a marked preference of V. paradoxa for specific soil conditions. These results of the aggregated classification of the shea parks in the study corroborate the work of Kelly *et al.* (2004). The latter indicated that the spatial distribution of shea trees becomes increasingly aggregated from cultivated areas to forests, passing through old fallow land, demonstrating that agricultural activities influence the type of spatial distribution of the species. Generally, the distribution of trees tends to become increasingly aggregated when moving from fields to older fallow land (Kelly, 2005). The heterogeneity of the environment and the low mobility, the weak dispersal capacities compared to the reproductive capacities, are possible causes which would explain the aggregative distribution in the shea parks studied.

In the shea parks studied, trees with large circumferences were more numerous in Sikolo (94.3%) than in Boniérédougou (81.9%). Trunk circumference measurements at 1.30 m above ground exceeded 76 cm or 0.76 m, the value determined by Guira (1997) for a mature, fruit-bearing tree. Furthermore, the diameter structure indicates that both groups of trees are old, but those in Sikolo are older.

The maximum height of shea trees in Sikolo is 15.34 m, with an average of 9.97 ± 1.53 m; in Boniérédougou, it is 14.38 m, with an average of 8.90 ± 1.82 m. 98.6% of the shea trees in Sikolo and 94% of those in Boniérédougou have heights exceeding 5 m, as determined by the Food and Agriculture Organization of the United Nations (FAO, 2020) for a mature tree. The large dimensions of the horizontal and vertical structures indicate the presence of individuals with large diameters and significant size. The modal class of diameters for shea trees ranges from 0.2 to.3 m in Boniérédougou and 0.3 to 0.4 m in Sikolo. Trees with a diameter of 0.5 to 0.6 m are commonly found in Sikolo and rarely observed in Boniérédougou. These results corroborate those of Ouédraogo and Devineau (1996) and Ouoba *et al.* (2023), who reported that large-diameter trees are rare in the Sudanian zone of Bondoukui and in the fallow lands of the northern Sudanian sector, and in the fields and fallow lands of the southern Sudanian sector of Burkina Faso. Contrary to the results of this study, Guimbo *et al.* (2010) reported that the frequency of shea trees with a diameter of 1.30 m > 60 cm is high (approximately 50%) in Birni N'Gaouré, in southwestern Niger. The vertical structure is also influenced by *V. paradoxa* individuals, the majority of which are concentrated in the 6–12 m and 8–14 m height classes in Boniérédougou and Sikolo, respectively. Furthermore, these authors noted that

V. paradoxa individuals in the parkland are clustered in the 7–14 m height class. Indeed, this study shows very few small trees and only a handful of large specimens; rather, medium-sized individuals are more prevalent. The bell-shaped structure (horizontal and vertical) of the two shea stands reflects a degraded population, characterized by a very low proportion of individuals in the small and very large classes. The conclusions of the work by Kaboré *et al.* (2012) are similar. They showed that the vertical structure of shea populations, in the different types of stands, varies from unbalanced to highly stable structures. The observed structural differences can be explained by abiotic factors such as rainfall, temperature, and soil, mentioned above.

The higher total biomass at Sikolo (6.74 ± 0.02 t DM/ha) compared to Boniérédougou (1.40 ± 0.00 t DM/ha) could be explained by the abundance of large-diameter trees. Indeed, the significant contribution of these trees to total biomass stocks has been established by other studies (Joosten *et al.*, 2004; Mbow, 2009). The agroforestry systems studied exhibited an abundance of large-diameter stems with a diameter at breast height (DBH) ≥ 20 cm (94.3%) at Sikolo and 81.9% at Boniérédougou. Furthermore, Mille and Louppe (2015) indicated that the biomass estimation of a forest stand is limited to that of trees with a DBH ≥ 10 cm. Also, the number of stems per unit area (density) would explain it more (Amougou *et al.,* 2016).

The carbon and atmospheric CO_2 equivalent stock obtained in the shea parkland of the Sudanian sector (Sikolo) was higher (3.17 ± 0.01 tC/ha and 11.62 ± 0.02 tCO_2/ha) than that of the Sudanian-Guinean sector (Boniérédougou) (0.66 ± 0.00 tC/ha and 2.41 ± 0.01 tCO_2/ha). This disparity observed among populations of the same species (*Vitellaria paradoxa* C.F. Gaertn.) can be explained by the demographic structure, the quantity of shea trees, the geographical area, and potentially by climatic (temperature and rainfall) and pedological (soil) factors. Indeed, previous work has shown that the carbon stock of woody species is closely linked to DBH and tree density (Chabi *et al.*, 2016; Dimobe *et al.*, 2018). However, in the context of this study, the Sudanian sector presented more individuals with large circumferences (dbh ≥ 50 cm ≈ 21.80% in Sikolo and dbh ≥ 50 cm ≈ 13.74% in Boniérédougou) and a high number of shea trees (57.17 stems/ha).

Furthermore, since carbon sequestration by trees in agroforestry systems is a function of the biomass available in these systems, the rate of carbon sequestration by agroforestry systems is subsequently a function of observations made at the biomass level. Agroforestry systems are also carbon dioxide (CO_2) reservoirs. The carbon sequestration capacity of the systems in the studied areas was estimated at 0.66 ± 0.00 and 3.17 ± 0.01 tC/ha for a total amount of CO_2 stored of 2.41 ± 0.01 and 11.62 ± 0.02 tCO_2/ha, respectively, in the Boniérédougou and Sikolo parks. The Sudanian sector agroecosystem proved to be the best CO_2 reservoir, with a sequestration rate of 11.62 ± 0.02 tCO_2/ha. However, our results (0.66 ± 0.00 and 3.17 ± 0.01 tC/ha) are lower than those obtained by Peltier *et al.* (2007), who found a carbon stock of 5.046 tC/ha in the aboveground biomass of a shea park in northern Cameroon. Furthermore, they remain significantly lower than the carbon stock contained in the aboveground woody and living parts of shea and Néré agroforestry systems in the Sudanian zone of Benin, which is 20.17 ± 4.19 tC/ha according to the results of the work by Saïdou *et al.* (2012). On the other hand, the quantity of 3.17 ± 0.01 tC/ha obtained in Sikolo is higher than that recorded (2.41 ± 0.01 tC/ha) in the Cordyla pinnata agroforestry park in the southern Groundnut Basin in Senegal (Diatta *et al.*, 2016a) and that recorded by Ilboudo (2018) (2.85 tC/ha) in the agroforestry zone of the forest massif of the National School of Water and Forestry in Burkina Faso. Furthermore, the polynomial type equation of Mbow (2009), with DBH as the only variable, was retained for the estimation of the aboveground biomass of trees and shrubs at the site of the National School of Water and Forests of Burkina Faso (Ilboudo, 2018.), while the IPCC method (2003), with 0.47 as the carbon fraction, was used in this study.

CONCLUSION

This study highlighted the characteristics and carbon sequestration potential of shea tree stands in agroforestry parks in Ivory Coast, specifically in the Hambol and Tchologo regions.

Shea trees are relatively present in the Hambol region, with a density of 15.52 trees/ha. *V. paradoxa* is more prevalent in the Tchologo region, with a high density of 57.18 shea trees per hectare. Furthermore, the horizontal and vertical structures of the trees in the Tchologo region (northeast) revealed individuals with large diameters (0.33 ± 0.10 m) and significant height (9.97 ± 1.53 m). Despite this characteristic difference, both agro-ecological zones (Hambol and Tchologo regions) exhibited the same distribution of shea trees, namely, an aggregated distribution.

Thus, the highest biomass quantity, 6.74 ± 0.02 t $DM.ha^{-1}$, and the largest carbon stock, 3.17 ± 0.01 t $C.ha^{-1}$, were recorded in the Sudanian savanna (Tchologo), demonstrating its adaptation to the soil and climate conditions and its carbon sequestration capacity across the phytogeographical sector, from the central to the northern part of the country.

Therefore, *V. paradoxa* should be prioritized in agricultural development policies for these areas. These agricultural policies should focus on establishing shea plantations (homogeneous or heterogeneous) or implementing agroforestry practices with shea as the main plant species.

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