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Vegetation Structure and Carbon Stocks of Two Protected Areas within the South-Sudanian Savannas of Burkina Faso

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Abstract: Savannas and adjacent vegetation types like gallery forests are highly valuable ecosystems contributing to several ecosystem services including carbon budgeting. Financial mechanisms such as REDD+ (Reduced Emissions from Deforestation and Forest Degradation) can provide an opportunity for developing countries to alleviate poverty through conservation of its forestry resources. However, for availing such opportunities carbon stock assessments are essential. Therefore, a research study for this purpose was conducted at two protected areas (Nazinga Game Ranch and Bontioli Nature Reserve) in Burkina Faso. Similarly, analysis of various vegetation parameters was also conducted to understand the overall vegetation structure of these two protected areas. For estimating above ground biomass, existing allometric equations for dry tropical woody vegetation types were used. Compositional structure was described by applying tree species and family importance indices. The results show that both sites collectively contain a mean carbon stock of $3.41 \pm 4.98 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}$. Among different savanna vegetation types, gallery forests recorded the highest mean carbon stock of $9.38 \pm 6.90 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}$. This study was an attempt at addressing the knowledge gap particularly on carbon stocks of protected savannas—it can serve as a baseline for carbon stocks for future initiatives such as REDD+ within these areas.

Keywords: aboveground biomass; degradation; gallery forest; West Africa; woody vegetation

1. Introduction

The population of Burkina Faso was recorded as 15.7 million in 2009. It is spread over an area of 274,000 km² and almost 80% of the population lives in rural areas and depends on agriculture as their main source of mainstay [1]. The population depends heavily on fuelwood as their main source of energy [2]. Moreover, livestock production and increases in population have put undue pressures on plant resources [3]. As a consequence, the vegetation structure and composition of the savanna habitats have been severely affected [4]. This degradation is further leading to challenges such as

food shortages, water scarcities, income losses, resource conflicts, and environmental deterioration [5]. Poverty and increasing need for food have resulted in agricultural expansions [6].

Burkina Faso can be divided into two main agro-ecological zones (i.e., Sahelian savanna and Sudanian savanna), categorized on the basis of isohyets and length of dry season [7]. The Sahelian savanna has a dry season of seven to nine months annually with annual rainfall of 600 mm. The Sudanian savanna has a dry season of four to seven months annually with annual rainfall of 750–1200 mm [8]. The Sahelian savanna can further be categorized into Northern Sahelian savanna (with annual rainfall of 600 mm and eight to nine months of dry season) and Southern Sahelian savanna (with annual rainfall of 600–750 mm and seven to eight months of dry season) [9]. Similarly, the Sudanian savanna can further be categorized into Northern Sudanian savanna (with annual rainfall of 750–1000 mm and six to seven months of dry season) and Southern Sudanian savanna (with annual rainfall of 1000–1200 mm and four to six months of dry season) [9].

Burkina Faso has a forest area of 19.6%, with additional 17.5% categorized as “other woodlands” [10]. The increasing pressure on forestry resources has resulted in a significant annual deforestation rate of 1.0% for the period 2010–2015 [10]. In addition, climate change constitutes a serious challenge which is undermining efforts towards sustainable development. Carbon sequestration can therefore serve as an essential strategy for the mitigation of climate change [11]. Forest resources, on the other hand, can be helpful in addressing climate vulnerabilities, such as food insecurity [12]. Reduced Emissions from Deforestation and Forest Degradation (REDD+) is a financial scheme focused upon reducing carbon emissions, which involves reducing emissions from deforestation and forest degradation, that is aimed towards the conservation and enhancement of forest carbon stocks, and a sustainable forest management including ecological and social targets [13]. Hence, REDD+ not only just provides developing countries the opportunity to tackle climate change by alleviating poverty but also helps by conserving their forest resources [14]. Moreover, it has also been identified as one of the economically most feasible mitigation options in tackling climate change [15]. The most important issue for REDD+ initiatives, however, is the estimation and the monitoring of the carbon stocks, and their success therefore largely depends on the availability of scientific information on forest carbon stocks [16]. Unfortunately, sufficient work on the quantification of carbon stocks in savannas does not exist [17]. Additionally, savannas have also been a major uncertainty in the carbon accounting of Africa [18].

The information on the composition and structural characteristics of the tree species in savannas are often lacking. Trees are considered an important component of vegetation and must be persistently monitored so that the forest successional processes can be managed for maintaining habitat diversity [19]. Such quantitative information can be helpful in developing appropriate conservation guidelines for the savannas. The composition and structural characteristics of the vegetation also help in understanding the magnitude of anthropogenic pressures on ecosystems. In Burkina Faso, like other countries in the world, protected areas were also established to safeguard the unique biodiversity for respective areas. Moreover, the protected areas also play an essential role in carbon sequestration [20]. Burkina Faso has 14% of its total land area categorized as protected areas and has future plans to increase the number to 30% [9].

The study therefore focused on assessing general composition and vegetation structure as well as the carbon stocks ($\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}$) in aboveground biomass (AGB_{dry}) of trees of typical vegetation types in two protected areas of Burkina Faso: Nazinga Game Ranch and Bontioli Nature Reserve. The main objective of this study is to provide a benchmark for future studies and baselines for future possible initiatives (e.g., REDD+), if initiated for these areas.

2. Materials and Methods

2.1. Study Area

Nazinga Game Ranch was created in 1979 (Figure 1) and is spread over an area of 97,536 ha at an average altitude of 280 m above sea level (asl) [21]. According to Burkina Faso’s legislation,

it has been classified as a protected area, listed as a “Wildlife Reserve” and it is very well known as a tourist destination [22]. There is a single dry season running from October to May and a single rainy season from June to September. It has a mean annual rainfall of 900 mm [23]. The average annual temperature is 27.1 °C. The Nazinga Game Ranch is traversed by Sessile River and its two tributaries (i.e., Dawevele and Nazinga Rivers); the rivers have characteristic seasonal flows. The vegetation has the characteristics of Southern Sudanian savanna. Typical species of the area include; shea tree (*Vitellaria paradoxa* C.F. Gaertn.), kodayoru tree (*Terminalia laxiflora* Engl. & Diels), female gardenia (*Gardenia erubescens* Stapf & Hutch.), lingahi tree (*Azelia africana* Sm.), and African birch (*Anogeissus leiocarpa* (DC.) Guill. & Perr.), among others [24].

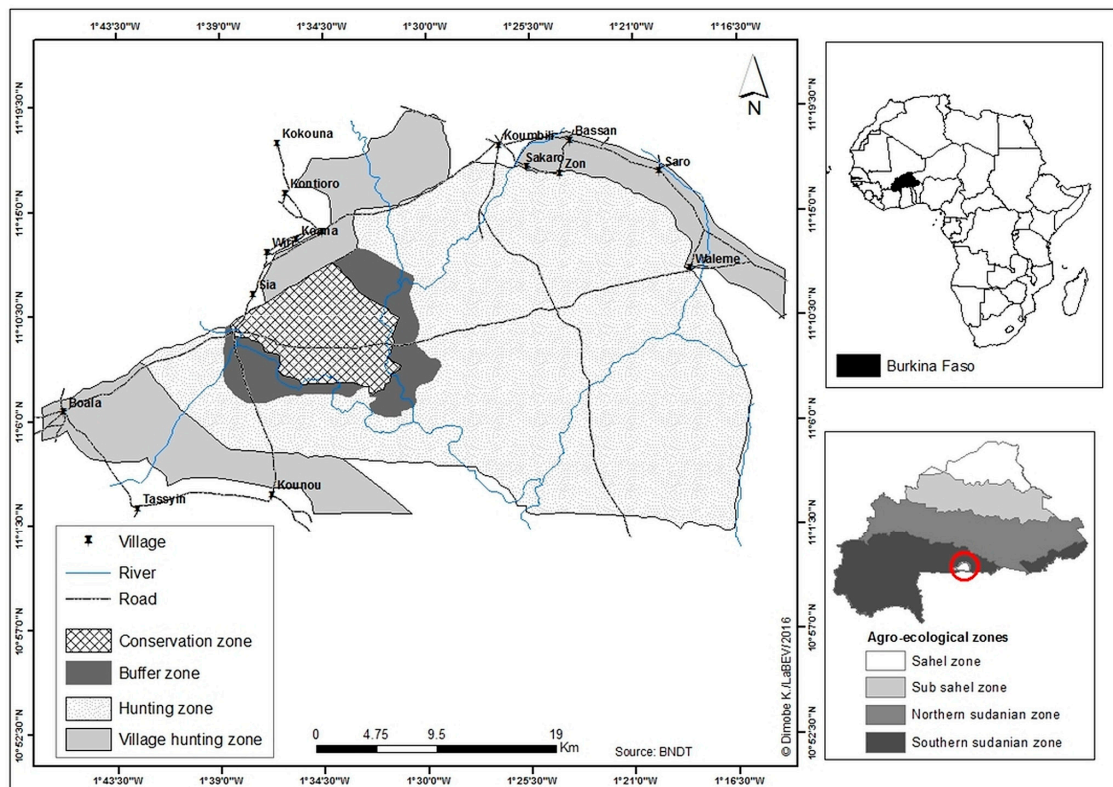


Figure 1. Nazinga Game Ranch, Burkina Faso.

For better management purposes, the Nazinga Game Ranch has been divided into four zones: (i) conservation zone; (ii) buffer zone; (iii) commercial hunting zone; and (iv) village hunting zone. The conservation zone consists of 9% and the buffer zone consists of 5% of the total area. The commercial hunting zone and the village hunting zone comprise the remaining 86% of the total area [21]. A few settlements are also located in the commercial hunting zone and village hunting zone. The area has once known to be one of the least populated areas in Burkina Faso, but has been subjected to increasing migrations after the Sahelian drought in the 1970s [23]. Agriculture is the mainstay for the local people and the major agricultural crops are corn (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), pearl millet (*Pennisetum glaucum* (L.) R. Br.), and peanut (*Arachis hypogaea* L.).

Bontioli Nature Reserve is also called “Forêt Classée de Bontioli” and is located in the Sudanian zone of southwestern Burkina Faso in the province of Bougouriba (Figure 2). It is a Category IV protected area, managed mainly for conservation through active management, according to International Union for Conservation of Nature (IUCN) Protected Areas Categories. It consists of the *Total Reserve* and the *Partial Reserve*. These areas were established by the territorial government during the colonial period based on two ministerial orders; (i) Order n° 3147/SE/EF of 23 March 1957, which was related to the demarcation of the area (29,500 ha) and the establishment of the *Partial Reserve* (ii) Order

3417/SE/EF of 29 March 1957, which was related to the demarcation of the area and classification of the Total Reserve (12,700 ha). The research study was confined to the *Total Reserve* only, as the *Partial Reserve* of Bontioli does not have consistent savanna cover due to being subjected to high pressure from human activities [25].

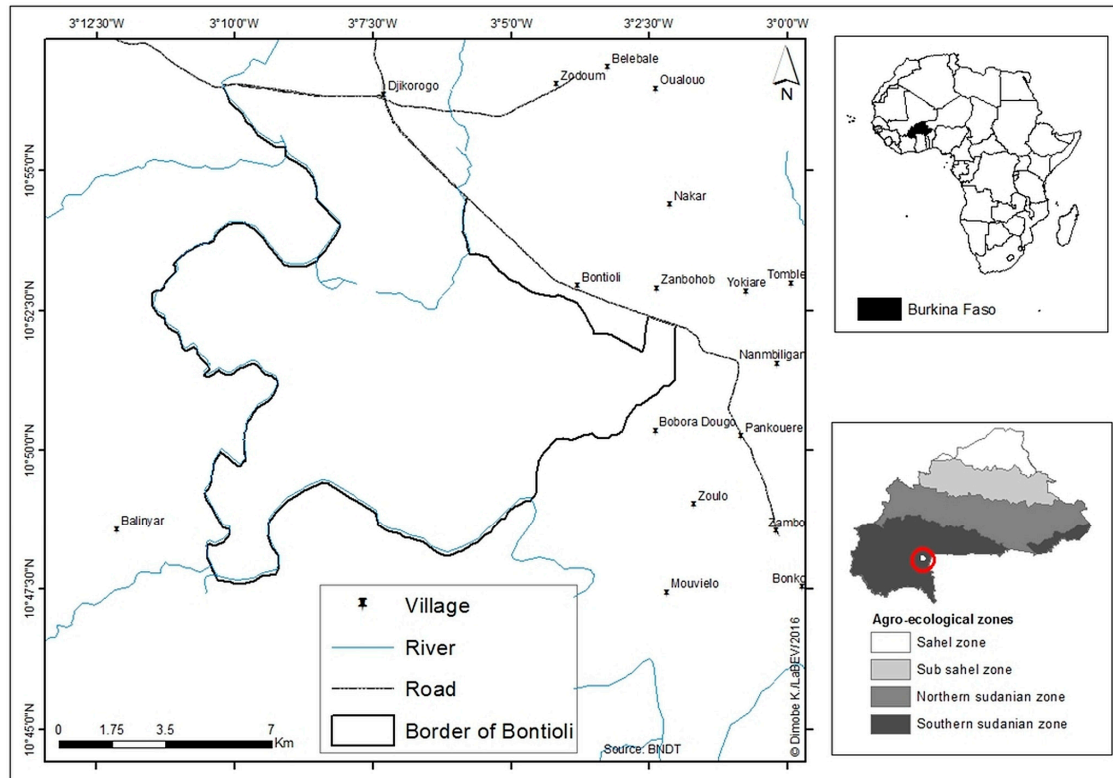


Figure 2. Bontioli Nature Reserve, Burkina Faso.

The vegetation of the Bontioli Nature Reserve also has the characteristics of the Southern Sudanian savanna. The rainfall varies between 900 and 1000 mm per year [25]. The rainy season ranges from May to October and the dry season spans from November to April [26]. The mean temperature has been recorded as 27.1 °C for the period of 2004–2006. The main river is the Bougouriba, which is pivotal for the hydrographical network within the Bontioli Nature Reserve [25]. The highest altitude for the Bontioli Nature Reserve has been recorded as 350 m asl and the lowest altitude as 250 m asl. The tree species include wild syringe (*Burkea africana* Hook.), barwood (*Pterocarpus erinaceus* Poir.), ordeal tree (*Crossopteryx febrifuga* (Afzel. ex G. Don) Benth.), and cangara tree (*Combretum glutinosum* Perr. ex DC).

2.2. Sampling Design

Due to the heterogeneous and overlapping landscape matrix a stratified sampling design was adopted for this study. The vegetation at both sites is classified as Southern Sudanian savanna [27]. The vegetation was further segregated into different types according to their physiognomy; (i) woodland savanna; (ii) tree savanna; (iii) shrub savanna; and (iv) gallery forest [28]. The tree and shrub savannas were categorized according to the *Yangambi* classification in 1956 [29]. Gallery forests were categorized as the narrow patches found along the fringes of semi-permanent water courses [30]. Woodland savannas were categorized on the basis of their close canopies and discontinuous grasses [31]. Twenty plots were established at either site, with five plots each per vegetation type. The plots were square-shaped and had a size of 20 m × 20 m, as suggested by [32].

2.3. Data Collection and Analysis

2.3.1. AGB_{dry} and Carbon Stock Estimation

The diameter at breast height (DBH) over bark for each tree ≥ 5 cm in every plot was measured with the help of the diameter tape at 1.3 m above ground level. In case of multi-stemmed trees, all stems with DBH above 5 cm were measured and the following formula was used for calculation of the respective total DBH [33];

$$DBH_{total} \text{ (cm)} = 2 \times \sqrt{(DBH_1)^2/2 + \dots + (DBH_n)^2/2} \quad (1)$$

The heights of the trees were estimated using Blume Leiss Hypsometer. The heights of trees less than two meters were measured with the help of a measuring tape. For multi-stemmed trees such as *Mitragyna inermis* (Willd.) Kuntze, the tip of the tallest stem was measured.

For tree AGB_{dry} estimation, the allometric equation suggested by [34] for dry forest stands was used, which is valid for DBH within the range of 5–156 cm;

$$AGB_{dry} \text{ (kg)} = 0.112 \times (\rho DBH^2 H)^{0.916} \quad (2)$$

where H = height (m) and ρ = Wood Density ($\text{g}\cdot\text{cm}^{-3}$).

The published wood densities were used for the AGB_{dry} estimation (Table A1). The wood densities at species or generic level were used subject to their availability [35]. The AGB_{dry} per plot was scaled up to $\text{Mg}\cdot\text{ha}^{-1}$. The AGB_{dry} (in $\text{Mg}\cdot\text{ha}^{-1}$) was converted to carbon stocks by multiplying with a carbon conversion factor of 0.5 [36].

2.3.2. Quadratic Mean Diameter and Density

The quadratic mean diameter for every plot was calculated as $\sqrt{(\sum d_i^2)/n}$ (d_i is DBH in cm for every tree and n refers to the total number of trees) [37]. The quadratic mean diameter is referred to as mean DBH throughout the document hereafter. The density was the total number of trees per plot per ha.

2.3.3. Basal Area (BA), Importance Value Index (IVI), and Family Importance Value (FIV)

The BA for each sampled tree was calculated as the following;

$$BA = (DBH/2)^2 \times \pi \times \text{expansion factor for ha} \quad (3)$$

IVIs were calculated from the species relative frequency (Rf), relative density (RDe), and relative dominance (RDo) [38];

$$Rf \text{ (\%)} = \frac{\text{Number of plots present with the species}}{\text{Total number of plots}} \times 100 \quad (4)$$

$$RDe \text{ (\%)} = \frac{\text{Number of individuals of a species}}{\text{Total number of individuals}} \times 100 \quad (5)$$

$$RDo \text{ (\%)} = \frac{\text{Total BA of a species}}{\text{Total BA for all species}} \times 100 \quad (6)$$

IVI for each species was calculated as the sum of Rf , RDe , and RDo . The FIVs were calculated from relative diversity (RDi), relative density (RDe), and relative dominance (RDo) according to [39];

$$RDi \text{ (\%)} = \frac{\text{Number of species in family}}{\text{Total number of species}} \times 100 \quad (7)$$

$$RDe \text{ (\%)} = \frac{\text{Number of trees in family}}{\text{Total number of trees}} \times 100 \quad (8)$$

$$RDo (\%) = \frac{\text{BA of family}}{\text{Total BA}} \times 100 \quad (9)$$

FIV for each family was eventually calculated as the sum of RDi , RDe , and RDo .

2.4. Statistical Analysis

To assess the normal distribution of different variables, the *Shapiro-Wilk-Test* was used. The means \pm Standard Deviations (*SD*) for averages of different variables per plot were calculated. As some data was not normally distributed, *Wilcoxon Rank Sum Test* was used for probing the statistical differences between two variables and *Kruskal Wallis Rank Sum Test* was used for more than two variables. The post-hoc analysis for significant differences in means was done using *Tukey's test*. A significance level of 0.05 was used for all statistical tests. The statistical analysis was performed and graphs were produced using the version 3.1.0 of R (R Foundation for Statistical Computing, Vienna, Austria) [40].

3. Results

3.1. DBH and Height

No significant difference was recorded between mean *DBHs* of two sites ($p > 0.05$). The mean *DBH*, however, differed significantly amongst the vegetation types for both sites collectively ($p < 0.05$). The mean *DBH* of gallery forests showed significant variation from the other vegetation types for both sites collectively ($p < 0.05$; Table 1). The gallery forests recorded the highest mean *DBH* of 48.80 ± 16.45 cm for both sites collectively. The *DBH* classes for both sites showed a reverse J-shape. For Nazinga Game Ranch, the highest number of the trees was recorded in the *DBH* class of 5 cm, forming 43.07% of the total (Figure 3). Together, 5 cm and 10 cm *DBH* classes formed 74.61% of the total stems for Nazinga Game Ranch. Similarly, for Bontioli Nature Reserve, 5 cm *DBH* classes formed 36.17% of the total and together 5 cm and 10 cm combined to form 68.08% of the total sampled stems (Figure 3).

Table 1. Structural characteristics of the four vegetation types at the study sites of Nazinga Game Ranch and Bontioli Nature Reserve.

Sites	Vegetation Types				Total
	Woodland Savanna	Tree Savanna	Gallery Forest	Shrub Savanna	
Nazinga Game Ranch					
Mean <i>DBH</i> (cm)	22.12 \pm 6.47	12.02 \pm 2.25	45.67 \pm 10.51	9.36 \pm 1.09	26.49 \pm 15.44
Mean tree height (m)	9.38 \pm 2.55	5.26 \pm 0.50	9.41 \pm 1.00	4.37 \pm 1.27	7.11 \pm 2.75
Mean Density (trees·ha ⁻¹)	160 \pm 8.31	80.5 \pm 7.52	73.75 \pm 8.98	11.25 \pm 1.62	325 \pm 60.99
Mean BA (m ² ·ha ⁻¹)	0.96 \pm 0.49	0.28 \pm 0.10	4.09 \pm 1.70	0.17 \pm 0.04	1.37 \pm 1.84
Mean Carbon (Mg·C·ha ⁻¹)	3.01 \pm 1.82	0.50 \pm 0.25	9.32 \pm 3.71	0.24 \pm 0.09	3.27 \pm 4.22
Mean <i>AGB</i> _{dry} (Mg·ha ⁻¹)	6.03 \pm 3.64	1.00 \pm 0.50	18.64 \pm 7.42	0.49 \pm 0.19	6.54 \pm 8.41
Bontioli Nature Reserve					
Mean <i>DBH</i> (cm)	19.72 \pm 4.24	12.94 \pm 2.90	49.61 \pm 23.00	13.66 \pm 6.98	30.15 \pm 18.19
Mean tree height (m)	9.17 \pm 1.45	6.49 \pm 0.40	9.52 \pm 1.81	4.62 \pm 1.99	7.45 \pm 2.50
Mean Density (trees·ha ⁻¹)	145 \pm 13.53	130 \pm 10.98	61.25 \pm 8.98	16.25 \pm 3.25	352.5 \pm 60.21
Mean BA (m ² ·ha ⁻¹)	1.05 \pm 0.41	0.45 \pm 0.27	5.25 \pm 5.26	0.36 \pm 0.41	1.78 \pm 2.33
Mean Carbon (Mg·C·ha ⁻¹)	3.13 \pm 1.14	0.98 \pm 0.66	9.45 \pm 9.66	0.67 \pm 0.76	3.56 \pm 3.41
Mean <i>AGB</i> _{dry} (Mg·ha ⁻¹)	5.92 \pm 2.74	1.42 \pm 0.42	18.91 \pm 19.33	1.24 \pm 1.61	6.87 \pm 11.63
Both Sites Collectively *					
Mean <i>DBH</i> (cm)	22.66 \pm 5.43a	13.73 \pm 3.59a	48.80 \pm 16.45b	11.74 \pm 4.95a	28.38 \pm 16.70
Mean tree height (m)	9.28 \pm 1.96a	5.88 \pm 0.77b	9.47 \pm 1.38a	4.50 \pm 1.58b	7.28 \pm 2.60
Mean Density (trees·ha ⁻¹)	305 \pm 10.70ac	210 \pm 10.32a	135 \pm 8.57ad	27.5 \pm 2.48b	677.5 \pm 117.40
Mean BA (m ² ·ha ⁻¹)	1.00 \pm 0.43a	0.37 \pm 0.21a	4.67 \pm 3.73b	0.27 \pm 0.29a	1.58 \pm 2.08
Mean Carbon (Mg·C·ha ⁻¹)	3.07 \pm 1.43a	0.74 \pm 0.53a	9.38 \pm 6.90b	0.45 \pm 0.56a	3.41 \pm 4.98
Mean <i>AGB</i> _{dry} (Mg·ha ⁻¹)	5.97 \pm 3.04a	1.21 \pm 0.49a	18.77 \pm 13.80b	0.86 \pm 1.15a	6.70 \pm 10.02

* Within rows (excluding "Total" column) of "Both Sites Collectively", means (\pm SD) not sharing a common lower case, differ significantly ($p < 0.05$) based on *Tukey's test* for comparison of means. *DBH*, diameter at breast height.

Similarly, no significant difference was recorded between mean heights of the two sites ($p > 0.05$). Significant difference was recorded amongst the vegetation types for both sites collectively ($p < 0.05$; Table 1). The mean heights of gallery forests and woodland savannas differed significantly from the tree and shrub savannas ($p < 0.05$; Table 1). The largest value of 9.47 ± 1.38 m for mean height was recorded for the gallery forests for both sites collectively (Table 1).

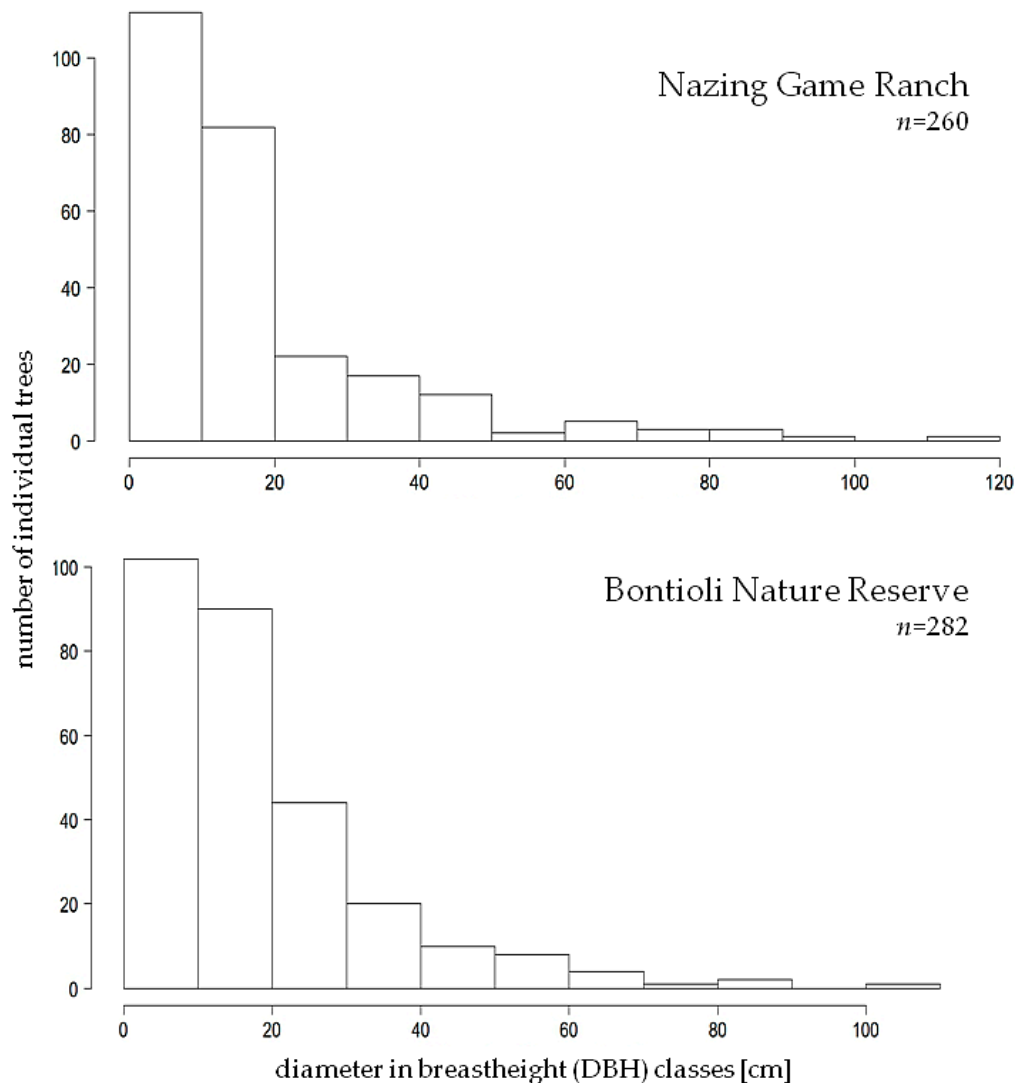


Figure 3. Distribution of individual trees in according DBH classes for both research sites, Nazinga Game Ranch (upper part) and Bontioli Nature Reserve (lower part).

3.2. Density and BA

No significant difference was recorded between mean densities of two sites ($p > 0.05$). Variation in mean densities of all vegetation types for both sites collectively was, however, recorded ($p < 0.05$). The highest mean density of 305 ± 10.70 trees·ha⁻¹ was recorded for the woodland savannas for both sites collectively (Table 1). Shrub savannas with mean density of 27.5 ± 2.48 trees·ha⁻¹ were significantly different from other vegetation types ($p < 0.05$; Table 1). The mean densities of woodland savannas and gallery forests were also significantly different from each other ($p < 0.05$; Table 1).

There was no significant difference between the mean BA for the two sites either ($p > 0.05$). Significant difference was recorded between vegetation types for both sites collectively ($p < 0.05$; Table 1). The mean BA for gallery forests was significantly different from other vegetation types for

both sites collectively ($p < 0.05$; Table 1). The highest mean BA of $4.67 \pm 3.73 \text{ m}^2 \cdot \text{ha}^{-1}$ was recorded for the gallery forests for both sites collectively (Table 1).

3.3. AGB_{dry}

No significant difference was recorded for the mean AGB_{dry} , for both sites collectively ($p > 0.05$). Significant difference in mean AGB_{dry} was recorded for the vegetation types for both sites collectively ($p < 0.05$; Table 1). The mean AGB_{dry} for gallery forests was significantly different from other vegetation types collectively for both sites ($p < 0.05$; Table 1). The overall mean AGB_{dry} for both sites collectively was $6.70 \pm 10.02 \text{ Mg} \cdot \text{ha}^{-1}$ (Table 1). Amongst vegetation types for both sites collectively, the highest mean AGB_{dry} was recorded for gallery forests, $18.77 \pm 13.80 \text{ Mg} \cdot \text{ha}^{-1}$ (Table 1).

3.4. Carbon Stocks

There was no significant difference between the mean carbon stocks of the two sites ($p > 0.05$). Significant difference, however, was recorded among the vegetation types collectively for both sites ($p < 0.05$; Table 1). The mean carbon stock for gallery forests was significantly different from other vegetation types for both sites collectively ($p < 0.05$; Table 1). The overall mean carbon stock for both sites collectively was recorded as $3.41 \pm 4.98 \text{ Mg} \cdot \text{C} \cdot \text{ha}^{-1}$ (Table 1). Gallery forests also showed the highest mean carbon stock, $9.38 \pm 6.90 \text{ Mg} \cdot \text{C} \cdot \text{ha}^{-1}$ (Table 1).

3.5. IVI, FIV, and Relative Abundance of Trees

Amongst the tree species for both sites collectively, *Anogeissus leiocarpa* was dominant with 28.04% (Table A1). *Mitragyna inermis* and *Vitellaria paradoxa* followed with 12.91% and 12.36%, respectively (Table A1). At Nazinga Game Ranch, the highest IVI of 115.56 was recorded for *Anogeissus leiocarpa* (Table A2). *Mitragyna inermis* and *Cassia sieberiana* followed with IVIs of 65.43 and 52.43, respectively (Table A2). At Bontioli Nature Reserve, the highest IVI was recorded for *Mitragyna inermis*, which was 98.59 (Table A2). *Vitellaria paradoxa* and *Combretum fragrans* followed with 43.55 and 35.75, respectively (Table A2).

The highest FIV in Nazinga Game Ranch was recorded for Combretaceae, 109.25 (Table A3). It was followed by Fabaceae-Caesalpiaceae, 56.50, and Rubiaceae, 48.12, respectively (Table A3). For Bontioli Nature Reserve, the highest FIV was also recorded for Combretaceae, 99.91 (Table A3). Rubiaceae and Fabaceae-Mimosoideae followed with 78.84 and 27.68, respectively (Table A3).

4. Discussion

4.1. DBH and DBH Class Distribution

The result for this study for mean DBH for gallery forests was not consistent with [31] who reported mean DBH of $15 \pm 3.84 \text{ cm}$. This difference could be attributed to their low sampling intensity. Similarly, the result of this study was also higher than what was reported by [41], which reported a mean DBH of $15.3 \pm 3.9 \text{ cm}$ for the unprotected site Yale, in southern Burkina Faso. The difference could be due to higher DBHs for gallery forests in this study. The DBH classes' distribution, representing a horizontal structure, showed a reverse J-shape for both the sites in this study. The reverse J-shape is typical for tropical and sub-tropical forests [42]. The reverse J-shape is also an indication of good regeneration of the woody vegetation community [43]. The highest number of trees was recorded in the DBH classes of 5 cm in our study for both the sites. The density decreased with increasing DBH classes. Savadogo, P. [25] also emphasized that with increasing DBH the density decreases.

4.2. Stem Densities, Tree Heights, and BA

Savadogo, P., et al. [31] reported gallery forests as having the highest mean stem density, which is contrary to the result of this study. Savadogo, P. [25] reported a mean density of $331 \text{ tree} \cdot \text{ha}^{-1}$ for the Bontioli Nature Reserve, which is close to the mean density for the Bontioli Nature Reserve for

this study. The result for this study for overall mean density is close to [41] for their mean density of 703 ± 49 trees·ha⁻¹.

The height measurements were consistent with other studies [25,31,43], however [25] emphasized that trees' heights are leveled down by anthropogenic pressures such as bushfires and wood cuttings. High values for mean BA for gallery forests were also confirmed [31,43].

4.3. AGB_{dry} and Carbon Stocks

This study revealed that mean AGB_{dry} and carbon stocks for Nazinga Game Ranch and Bontioli Nature Reserve were not significantly different. This can be attributed to the mean $DBHs$ and mean heights which were also not significantly different between the two sites. Overall, the similarity between the two sites, as shown statistically, could be attributed to the similar environmental conditions. To the authors' knowledge, there are no AGB_{dry} and carbon stock estimates available for these two sites. Previous estimates would have helped in comparison with results of this study. Lewis, S.L. et al. [44] also emphasized that only very few carbon stock estimates based on field inventories are available for West Africa. Estimates for carbon stocks have been provided by [8] for all of Burkina Faso, but this data was not comparable with this study because of the national level focus on different land uses categorized according to [45].

In this study, the highest overall mean carbon stock was recorded for gallery forests. The mean carbon stock of gallery forests was also significantly different from other vegetation types. This significant difference could be attributed to their mean DBH , which was also the highest amongst the vegetation types. The gallery forests were mainly comprised of *Mitragyna inermis*. This species was the second most abundant species amongst all the species collectively from both sites. *Mitragyna inermis* was mainly found in clumps and was mostly comprised of multi-stem trees. It can be assumed that the calculation of the DBH of *Mitragyna inermis*, through the Equation (1) used in this study, may have resulted in an overestimation for $DBHs$ for gallery forests and hence in the overall mean carbon stock estimation. There is no statistical difference among the remaining vegetation types: the mean DBH of woodland savannas was not significantly different from the tree and shrub savannas either. However, the density of woodland savannas was higher than the other two.

Sawadogo, L., et al. [46] reported AGB_{dry} , through destructive sampling, for *Anogeissus leiocarpa*, *Combretum glutinosum*, *Detarium microcarpum*, *Entada africana*, and *Piliostigma thonningii* as 320.95 kg, 42.26 kg, 61.74 kg, 32.16 kg, and 29.42 kg, respectively, for the sites of Laba and Tiogo State Forests, located in transition from the north to south Sudanian zone in Burkina Faso. The estimates for AGB_{dry} for this study were only consistent with [46] for *Entada africana* (30.94 kg) in the Bontioli Nature Reserve. Estimates were not consistent in the case of *Anogeissus leiocarpa* (168.34 kg and 508.64 kg for Nazinga Game Ranch and Bontioli Nature Reserve, respectively); for *Combretum glutinosum* (19.03 kg) for Bontioli Nature Reserve; for *Detarium microcarpum* (37.87 kg) for Nazinga Game Ranch; and for *Piliostigma thonningii* (14.21 kg and 11.61 kg for Nazinga Game Ranch and Bontioli Nature Reserve, respectively). Inconsistencies between estimates of AGB_{dry} between two studies could be because of the variability of basic wood density in the individuals of the same species for different geographical locations and ages [47]. Karlson, M., et al. [48] reported AGB_{dry} of 15.96 Mg·ha⁻¹ for Saponé, central Burkina Faso. They included open woodlands, agroforestry parklands, small scale tree plantations, and dense forest patches in their study. These stands are often characterized by trees of bigger sizes, which could be the reason why higher AGB_{dry} estimates were recorded for them in comparison to this study. The result for this study for mean carbon stock for both sites collectively was higher than [49] who reported 1.10 ± 0.32 Mg·C·ha⁻¹ for natural vegetation with high degradation for Bale province, south Sudanian zone, western Burkina Faso—where they used the same generalized allometric equation for estimation of AGB_{dry} given by [34], Equation (2), which was used for this study.

4.4. Floristics

The results of this study for Combretaceae and Rubiaceae as the most abundant families for both sites collectively is consistent with [25,31,41,50]. The most common families in this study were Combretaceae, Rubiaceae, and Fabaceae-Caesalpiniaceae, which portrays a typical taxonomic pattern of savanna-woodland mosaics in Africa and for the northern Sudanian zone in Burkina Faso [51].

Savadoogo, P., et al. [31] reported the highest IVI of 214.50 for *Mitragyna inermis*, which is also consistent with the result for Nazinga Game Ranch for this study. The high IVI for *Mitragyna inermis* in this study for Nazinga Game Ranch may also suggest that gallery forests are less affected by human disturbances [50,52]. Karlson, M., et al. [48] reported 37 species for their study site at Saponé, central Burkina Faso, which is close to 29 species collectively for both sites in this study. Species such as *Detarium microcarpum* and *Lannea microcarpa* were amongst the rarest recorded for both sites collectively in this study. This could be attributed to the preferences of local inhabitants at both sites for these two species for the associated multiple benefits which can be derived from them [25]. The highest number of 140 individuals was recorded for *Anogeissus leiocarpa* for Nazinga Game Ranch against a contrasting 12 trees for Bontioli Nature Reserve. This drastic difference could be due to the proximity of this species to the settlements in Bontioli Nature Reserve. *Anogeissus leiocarpa* is known for its medicinal qualities and hence could be the subject of prodigious cutting in Bontioli Nature Reserve [53].

5. Conclusions

The highest mean AGB_{dry} and highest mean carbon stock were recorded for Bontioli Nature Reserve, however, statistically there was no significant difference recorded between the two investigated sites for these two variables. Significant difference was recorded between the vegetation types collectively for both sites where the highest mean AGB_{dry} and the highest mean carbon stock were recorded for gallery forests. The highest FIV was recorded for Combretaceae for both of the sites. The highest IVIs were recorded for *Anogeissus leiocarpa* and *Mitragyna inermis* for the sites of Nazinga Game Ranch and Bontioli Nature Reserve, respectively.

This study contributes in addressing the knowledge gap on carbon stocks of protected savannas in West Africa. To the authors' knowledge, it was a first attempt to estimate the AGB_{dry} and carbon stocks of different vegetation types at the two protected areas of Nazinga Game Ranch and Bontioli Nature Reserve. The results of this study can therefore serve as a benchmark for future studies and baselines for future possible payment for environmental initiatives and REDD+ programmes, if initiated for these areas. This study also provides insights that can be useful for areas with similar environmental settings.

It is suggested that land use and land cover change analysis and carbon inventories over different time periods should be conducted at these two sites in the future, as they can also provide a good picture of deforestation and degradation at these two sites. [28], for instance, have reported losses of vegetation cover over the past 29 years as a result of agriculture expansion at Bontioli Nature Reserve through land use and land cover change analysis using remote sensing and questionnaire surveys combined. A similar study for Nazinga Game Ranch, where there are also reports of high dependency of local communities on the vegetation [22], would also be helpful for the identification of drivers responsible for deforestation and degradation.

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Author Contributions: Mohammad Qasim conducted the field work and contributed to the analysis of the data as well as in writing the first draft and revising the manuscript. Stefan Porembski co-developed the study design, supervised the floristic data analysis and contributed in revising the manuscript. Dietmar Sattler developed and supervised the biomass data analysis and contributed to writing the first draft and revising the manuscript. Katharina Stein co-developed the study design, supervised the field work on site and contributed in revising the manuscript. Adjima Thiombiano provided floristic data and contributed to the overall literature review and in revising the manuscript. Andre Lindner developed the study design and contributed in writing the first draft and revising the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Species represents the tree species at both sites of Nazinga Game Ranch and Bontioli Nature Reserve collectively. *N* = number of trees for each species. Relative abundance (%) (percentage of tree species individuals relative to the total number of trees). Wood density represents the published values of wood densities at species and generic levels for all the trees at both sites.

Species	<i>N</i>	Relative Abundance (%)	Wood Density (g·cm ⁻³)		References
			Species Level	Generic Level	
<i>Acacia sieberiana</i> DC. var. <i>villosa</i> A. Chev.	2	0.36	0.65		[54]
<i>Azelia africana</i> Sm.	1	0.18	0.71		[55]
<i>Anogeissus leiocarpa</i> (DC.) Guill. & Perr.	152	28.04	0.73		[55]
<i>Bridelia scleroneura</i> Müll. Arg.	3	0.55		0.81	[56]
<i>Cassia sieberiana</i> DC.	16	2.95	0.72		[57]
<i>Combretum adenogonium</i> Steud. ex A. Rich.	13	2.39	0.64		[58]
<i>Combretum collinum</i> Fresen.	8	1.47	0.79		[54]
<i>Combretum fragrans</i> F.Hoffm.	37	6.82	0.64		[58]
<i>Combretum glutinosum</i> Perr. ex DC.	2	0.36	0.90		[59]
<i>Daniellia oliveri</i> (Rolfe) Hutch. & Dalz.	13	2.39	0.40		[60]
<i>Detarium microcarpum</i> Guill. & Perr.	4	0.73	0.78		[61]
<i>Diospyros mespiliformis</i> Hochst. ex A. DC.	1	0.18		0.72	[57]
<i>Entada africana</i> Guill. & Perr.	7	1.29	0.53		[57]
<i>Gardenia erubescens</i> Stapf & Hutch.	1	0.18	0.64		[54]
<i>Gardenia ternifolia</i> Schum. & Thonn.	3	0.55	0.81		[56]
<i>Lannea microcarpa</i> Engl. & K. Krause	1	0.18	0.51		[57]
<i>Maytenus senegalensis</i> (Lam.) Exell	2	0.36		0.71	[62]
<i>Mitragyna inermis</i> (Willd.) O. Ktze.	70	12.91		0.56	[62]
<i>Parkia biglobosa</i> (Jacq.) R. Br. ex G. Don f.	17	3.13	0.61		[63]
<i>Pericopsis laxiflora</i> (Benth. ex Bak.) van Meeuwen	1	0.18		0.93	[64]
<i>Ptilostigma thonningii</i> (Schum.) Milne-Redhead	9	1.66	0.61		[57]
<i>Pseudocedrela kotschyi</i> (Schweinf.) Harms	7	1.29	0.62		[65]
<i>Pterocarpus erinaceus</i> Poir.	4	0.73	0.62		[57]
<i>Saba senegalensis</i> (A. DC.) Pichon	6	1.10		0.62	[57]
<i>Stereospermum kunthianum</i> Cham.	3	0.55	0.60		[58]
<i>Terminalia laxiflora</i> Engl. & Diels	65	11.99		0.71	[62]
<i>Terminalia macroptera</i> Guill. & Perr.	23	4.24		0.71	[62]
<i>Vitellaria paradoxa</i> C.F. Gaertn.	67	12.36	0.72		[66]
<i>Ximenia americana</i> L.	4	0.73	0.95		[59]

UNFCCC = United Nations Framework Convention on Climate Change.

Table A2. Importance Value Index (IVI) of tree species at Nazinga Game Ranch and Bontioli Nature Reserve. *Rf* (%) is the relative frequency of tree species, *RDe* (%) is the relative density of trees species, and *RDo* (%) is the relative basal area of the tree species.

Nazinga Game Ranch				
Species	<i>Rf</i> (%)	<i>RDe</i> (%)	<i>RDo</i> (%)	IVI
<i>Afzelia africana</i> Sm.	5	0.38	0.67	6.06
<i>Anogeissus leiocarpa</i> (DC.) Guill. & Perr.	35	53.84	26.72	115.56
<i>Cassia sieberiana</i> DC.	30	6.15	16.28	52.43
<i>Detarium microcarpum</i> Guill. & Perr.	10	1.53	0.25	11.79
<i>Diospyros mespiliformis</i> Hochst. ex A. DC.	5	0.38	0.04	5.43
<i>Maytenus senegalensis</i> (Lam.) Exell	10	0.76	0.08	10.85
<i>Mitragyna inermis</i> (Willd.) O. Ktze.	25	8.84	31.58	65.43
<i>Parkia biglobosa</i> (Jacq.) R. Br. ex G. Don f.	5	0.38	5.13	10.51
<i>Piliostigma thomningii</i> (Schum.) Milne-Redhead	5	0.38	0.06	5.44
<i>Saba senegalensis</i> (A. DC.) Pichon	15	2.30	14.17	31.48
<i>Stereospermum kunthianum</i> Cham.	5	0.38	0.03	5.42
<i>Terminalia laxiflora</i> Engl. & Diels	25	11.15	2.14	38.29
<i>Vitellaria paradoxa</i> C.F. Gaertn.	25	13.46	2.78	41.25
Bontioli Nature Reserve				
Species	<i>Rf</i> (%)	<i>RDe</i> (%)	<i>RDo</i> (%)	IVI
<i>Acacia sieberiana</i> DC. var. <i>villosa</i> A. Chev.	5	0.70	0.16	5.87
<i>Anogeissus leiocarpa</i> (DC.) Guill. & Perr.	15	4.25	6.12	25.38
<i>Bridelia scleroneura</i> Müll. Arg.	5	1.06	0.51	6.57
<i>Combretum adenogonium</i> Steud. ex A. Rich.	15	4.60	2.00	21.61
<i>Combretum collinum</i> Fresen.	5	2.83	0.50	8.33
<i>Combretum fragrans</i> F.Hoffm.	15	13.12	7.62	35.75
<i>Combretum glutinosum</i> Perr. ex DC.	10	0.70	0.10	10.81
<i>Daniellia oliveri</i> (Rolfe) Hutch. & Dalz.	15	4.60	9.63	29.24
<i>Entada africana</i> Guill. & Perr.	10	2.48	0.51	12.99
<i>Gardenia erubescens</i> Stapf & Hutch.	5	0.35	0.06	5.41
<i>Gardenia ternifolia</i> Schum. & Thonn.	10	1.06	0.72	11.78
<i>Lannea microcarpa</i> Engl. & K. Krause	5	0.35	0.26	5.61
<i>Mitragyna inermis</i> (Willd.) O. Ktze.	35	16.66	46.93	98.59
<i>Parkia biglobosa</i> (Jacq.) R. Br. ex G. Don f.	10	5.67	5.09	20.77
<i>Pericopsis laxiflora</i> (Benth. ex Bak.) van Meeuwen	5	0.35	0.18	5.53
<i>Piliostigma thomningii</i> (Schum.) Milne-Redhead	20	2.83	0.31	23.15
<i>Pseudocedrela kotschyi</i> (Schweinf.) Harms	10	2.48	1.59	14.07
<i>Pterocarpus erinaceus</i> Poir.	5	1.41	3.39	9.81
<i>Stereospermum kunthianum</i> Cham.	5	0.70	0.05	5.76
<i>Terminalia laxiflora</i> Engl. & Diels	20	12.76	2.92	35.69
<i>Terminalia macroptera</i> Guill. & Perr.	5	8.15	3.73	16.89
<i>Vitellaria paradoxa</i> C.F. Gaertn.	25	11.34	7.20	43.55
<i>Ximenia americana</i> L.	15	1.41	0.30	16.72

Table A3. FIV of Nazinga Game Ranch and Bontioli Nature Reserve. *RDi* (%) is the relative diversity of the plant family, *RDe* (%) is the relative density of the plant family and *RDo* (%) is the relative basal area of the plant family.

Nazinga Game Ranch				
Family	<i>RDi</i> (%)	<i>RDe</i> (%)	<i>RDo</i> (%)	FIV
Apocynaceae	7.69	2.30	14.17	24.17
Bignoniaceae	7.69	0.38	0.03	8.11
Fabaceae-Caesalpiniaceae	30.76	8.46	17.27	56.50
Celastraceae	7.69	0.76	0.08	8.54
Combretaceae	15.38	65	28.86	109.25
Ebenaceae	7.69	0.38	0.04	8.12
Fabaceae-Mimosoideae	7.69	0.38	5.13	13.21
Rubiaceae	7.69	8.84	31.58	48.12
Sapotaceae	7.69	13.46	2.78	23.94
Bontioli Nature Reserve				
Family	<i>RDi</i> (%)	<i>RDe</i> (%)	<i>RDo</i> (%)	FIV
Anacardiaceae	4.34	0.35	0.26	4.96
Bignoniaceae	4.34	0.70	0.05	5.11
Fabaceae-Caesalpiniaceae	8.69	7.44	9.95	26.09
Combretaceae	30.43	46.45	23.02	99.91
Euphorbiaceae	4.34	1.06	0.51	5.92
Fabaceae-Papilionoideae	8.69	1.77	3.58	14.04
Meliaceae	4.34	2.48	1.59	8.42
Fabaceae-Mimosoideae	13.04	8.86	5.77	27.68
Olaceae	4.34	1.41	0.30	6.07
Rubiaceae	13.04	18.08	47.72	78.84
Sapotaceae	4.34	11.34	7.20	22.89

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