

The contribution of small and medium diameter trees to biomass and carbon pools in Yabo, Sokoto State, Nigeria

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Abstract

Increases in human population and human activities have led to corresponding increases in the amount of atmospheric carbon dioxide. The present rates, by far, supersede historical records, and by 2050, the global concentration is expected to reach 470 ppm even if the average concentration is controlled at 2 ppm per annum. Trees and vegetation, in general, perform the ecosystem service of storing and sequestering atmospheric carbon. However, it is widely believed that larger-diameter trees store more biomass and carbon stocks. This study assessed the contribution of small- and medium-diameter trees to regional carbon pools of the West African Savanna, using a general allometric equation. A total of 671 woody stems of ≥ 2 m height and ≥ 5 cm diameter, belonging to 40 species, 35 genera, and 19 families, were identified. The trees stored 120.2 kg of carbon stock, which translated to approximately 0.18 kg/tree. Although most of the trees enumerated in the study have small to medium diameters, few large-diameter trees including *Combretum ghasalense* (1.23 kg/tree), *Ceiba pentandra* (1.08 kg/tree), *Faidherbia albida* (0.92 kg/tree), and *Prosopis africana* (0.73 kg/tree) contributed the highest mean carbon stock in the area. The study confirms that larger-diameter trees account for much of biomass and carbon in a given area, but this does not underscore the contribution of smaller trees to the regional carbon stock especially in dry environments where they form a greater percentage of available trees. The study recommends the conservation of small- and medium-diameter trees to ensure the sustainability of this relatively dry environment.

Keywords: biomass, carbon, carbon pool, tree diameter, West African Savanna

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1. Introduction

Carbon dioxide (CO₂) is the most important anthropogenic greenhouse gas (GHG) in the atmosphere and contributes approximately 84% of the global radiative forcing [1]. This GHG, which is primarily produced from human activities, especially combustion of fossil fuels and cement production [1, 2], accounts for 60% of the observed global warming [3]. Together with other GHGs, predominantly methane (CH₄) and sulfur dioxide (SO₂), this gas not only warms the global atmosphere by trapping certain wavelengths of radiation [4] but also destroys the protective atmospheric ozone layer.

With the increasing global population and increased human activities, the concentration of CO₂ in the atmosphere has been on the rise at unprecedented rates [5]. By 2020, its concentration had risen to 48% above its preindustrial level (before 1750). By the end of 2022, data from the Earth System Research Laboratories (ESRL) of the National Oceanic and Atmospheric Administration (NOAA) (<https://gml.noaa.gov/>) indicated that the atmospheric concentration of CO₂ was 417.2 ppm, which translates to about 50% of the preindustrial levels. This is expected to reach

685 ppm by 2050 [6] and about 470 ppm even if the average global concentration is controlled at 2 ppm per annum [7].

The African savannas and dry forests constitute the largest land area in the tropics and Africa in particular [8, 9]. They house diverse ecosystems with a wide range of woody cover [10] and are important sinks of biomass and carbon stocks [11, 12]. Hence, they play a vital role in the global carbon budget and carbon cycling among the atmosphere, vegetation, and soil [13]. The total carbon of trees in Sub-Saharan Africa was estimated at 0.84 ($\pm 19.8\%$) Pg C with average carbon stocks of individual trees ranging from 0.54 Mg C ha⁻¹ and 63 kg C tree⁻¹ in the arid zone to 3.7 Mg C ha⁻¹ and 98 kg tree⁻¹ in the subhumid zone [14]. However, only a few studies [8, 15–17] were conducted across the continent. It could therefore be asserted that the biomass and carbon stocks of Africa are not adequately studied and, thus, poorly quantified [9, 12, 18]. This, to some extent, prevents their inclusion in global analyses [19] and creates large uncertainties regarding the size of standing carbon stocks in the continent [20].

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Trees are an important component of ecosystem health and provide environmental, social, and economic benefits to people. These include modifying the micro-climate by lowering surface and air temperature, storing and sequestering carbon, and providing provisioning services in the form of food, fuelwood, animal fodder, and shade and habitat for many organisms [21]. One of the most important functions of trees and plants, in general, is the storage and sequestration of biomass and carbon dioxide (CO₂) in both aboveground and belowground biomass [22, 23]. Assessment of biomass and carbon storage of trees is crucial for understanding the role of forest ecosystems as carbon sinks and for sustainable forest management [16], especially in the face of ongoing climate crisis [24].

The assessment of tree biomass and carbon stock involves the direct (or harvest) and indirect methods. The former method, which is laborious, time-consuming, and expensive [20, 25, 26], involves cutting down all trees and weighing the oven-dried mass of the various components to arrive at stem biomass [27]. The latter method, on the other hand, relies on remote sensing and/or allometric equations, which may be general or species-/site-specific to estimate tree biomass using a number of variables including tree diameter, diameter and height, or a combination of diameter, height, and wood density [20, 22, 28, 29]. This is based on the assertion that tree carbon depends on wood density, tree height, and stem diameter, among other things [8].

Tree species' diameter at breast height (DBH) is one of the most popular indices considered while estimating the aboveground biomass (AGB) and carbon storage of trees in forests and other vegetated areas [16, 17, 27, 30–32], particularly in Africa [33]. Using DBH alone as the predictor variable produces the most accurate and stable regional AGB estimates [27, 34], and reduces uncertainties as it correlates with all components of species such as *Pterocarpus erinaceus* [18] and doesn't require tree height measurements [35]. DBH is therefore the most common independent variable found in most allometric models [36].

It is a widely held view that positive correlation exists between the diameter of individual stems and the amount of tree biomass [37] and that the amount of biomass and carbon stored and sequestered by trees is a function of their diameter [38] since trees store more CO₂ by assimilating it in their woody tissue as they grow [39]. Accordingly, large-diameter trees contribute more biomass and carbon stock to the total carbon pool than trees with comparatively smaller diameters [31, 40–44]. Large-diameter trees contribute approximately 41% of the world's AGB [42] and about 44.5% in Africa [45]. As such, most studies focus on relatively large- and medium-diameter trees (≥4 cm diameter), overlooking or relegating the contribution of trees with small diameter [19, 22, 46], especially in tropical Africa where they are important to demographic rates and nutrient cycling [47]. This study therefore attempted to evaluate the contribution of small-diameter trees to regional biomass and carbon stocks, and their role in enhancing climate change resilience.

2. Materials and methods

2.1. The study area

The study was conducted on a 32 km² land around Yabo town (Latitudes 12° 41'45.5" N to 12° 44'51.3" N and Longitudes 04° 58'54.2" E to 05° 02'7.9" E) in the Yabo Local Government area,

Sokoto State, Nigeria. It is a mosaic of native forest and shrubland that has been extensively modified by human activities including expansion of built-up and farming areas, fuelwood exploitation, and overgrazing. The Yabo Local Government shares borders with Silame, Wamakko, and Bodinga Local Government areas in the north, Tambuwal Local Government to the southwest, and Shagari Local Government to the east and southeastern parts (**Figure 1**).

This area lies within the Sudano-Sahelian zone where the climate is generally variable. The mean annual temperature ranges between 20°C and 36°C in the north and 22°C and 26°C in the south, while rainfall, which traditionally follows latitudinal gradient, ranges between 200 mm in the north and 1,000 mm in the south [48]. Vegetation of the area is comprised of sparse woody cover of drought-tolerant, perennial species such as *Acacia* in the north and grassland savannas characterized by annual grasses and parkland landscapes in the south. However, the density and height of species generally decrease in a south–north direction [49, 50].

2.2. Sampling and data collection

A total of 50 plots of 30 × 30 m dimension were used for the study. These plots were randomly generated across the study area using the sampling facility of Idrisi TerrSet software (**Figure 2**). The coordinates of each point were recorded in a Garmin 78S GPS and traced in the field. Data for the study were collected plotwise, and thus, all woody species (≥2 m height and ≥5 cm diameter) encountered in the respective plots were identified and recorded, following the methods of Hutchinson and Dalziel [51]. Tree height was measured with a clinometer, while tree diameter was measured at breast height (1.3 m above the ground) with a diameter tape. If a tree forks within 1.3 m, the forks were considered different stems and thus, measured individually [12, 46, 52, 53]. In the same vein, buttressed trees were measured where the cylindrical bole started, as obtained by Nolke et al. [54]. Following McNicol et al. [12], trees were classified as small diameter (5–15 cm), medium diameter (15–40 cm), and large diameter (>40 cm).

2.3. Data analysis

In this study, the general allometric equation was adopted from Chave et al. [20], which is one of the two standard models for estimating AGB and carbon stock in tropical forests. This model has been found to give more accurate estimates of biomass and carbon stock in tropical areas [55] compared to other equations that use diameter alone [56, 57] or diameter and height [58, 59]. In addition, the equation has been widely used in Africa and other areas with similar climatic characteristics [60, 61]. The other model developed by Mokany et al. [62] is typically suitable for moist tropical environments [63]. Tree biomass and carbon stock were estimated based on height, diameter, and wood density as follows:

$$AGB = 0.0673 \times (\rho D^2 H)^{0.976} \quad (1)$$

where

ρ = Wood density (g cm⁻³)

D = Diameter at breast height (cm)

H = Height (m)

The wood density (ρ) for all (except three) species was obtained from the Global Wood Density Database [64] and the World Agroforestry Database [65]. Wood density or specific gravity (ρ) is a basic characteristic of trees and an important predictor of AGB [20, 36]. Thus, it is an important parameter used to estimate tree biomass and its corresponding carbon stocks [66]. This, however, varies markedly between tree species, diameter class, life history strategies, and environmental gradients [64].

Most of the allometric equations used in the AGB estimation were derived from forest trees that have more biomass than the urban, open-grown trees. To account for this difference, therefore, the results were multiplied by a conversion factor of 0.8 [67]. This was then multiplied by 0.5 to obtain carbon stock as suggested by IPCC [68] and as obtained from other previous studies [35, 69–72]. This calculation is based on the notion that carbon constitutes 50% of the total wood biomass [38, 73–76].

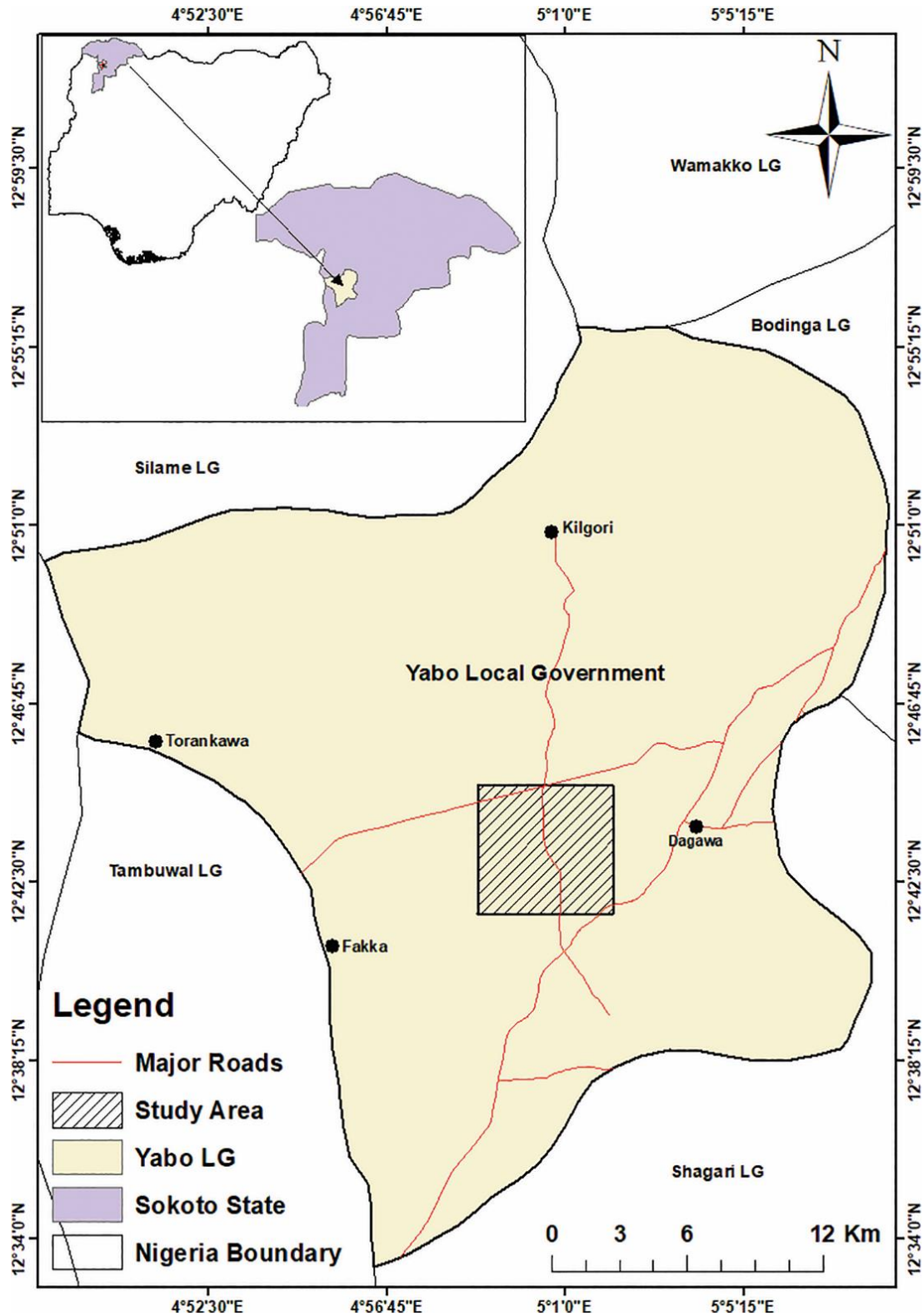


Figure 1 • The study area in Yabo Local Government, Sokoto State. LG, Local Government.

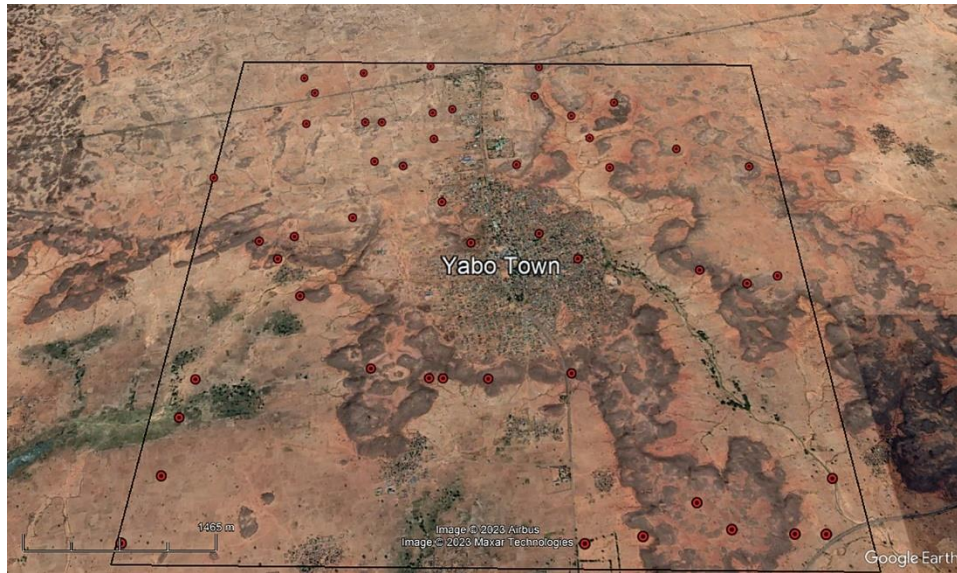


Figure 2 • Study plots generated for the study.

3. Results

3.1. Floristic composition

The study recorded 671 woody stems of ≥ 2 m height and ≥ 5 cm diameter, belonging to 40 species, 35 genera, and 19 families. Of particular importance in the species composition of the area is *Azadirachta indica* (A. Juss), which belongs to the family Meliaceae.

This species contributed 95 stems, comprising 14.15% of all the stems enumerated in the study. The prominence of *Azadirachta indica* in the area may not be unconnected with its introduction and wider propagation in the colonial forestry program as a source of firewood and shade [51] and for desertification control [77] in Northern Nigeria (**Table 1**).

Table 1 • Floristic composition in the area

| S/N | Species | Family | Local name | No. of stems |
|-----|--|-----------------|----------------|--------------|
| 1 | <i>Acacia macrostachya</i> Reichenb. ex Benth. | Fabaceae | Gardaye | 24 |
| 2 | <i>Acacia nilotica</i> (Linn.) Willd. ex Del. | Fabaceae | Bagaruwa | 5 |
| 3 | <i>Acacia sieberiana</i> var. Woodii | Fabaceae | Farar Kaya | 8 |
| 4 | <i>Anogeissus leiocarpus</i> (DC.) Guill. & Perr | Combretaceae | Marke | 1 |
| 5 | <i>Azadirachta indica</i> A. Juss | Meliaceae | Dogon Yaro | 95 |
| 6 | <i>Balanites aegyptiaca</i> (Linn.) DeI. | Balanitiaceae | Aduwa | 21 |
| 7 | <i>Boscia angustifolia</i> A. Rich. | Capparidiaceae | Anza | 12 |
| 8 | <i>Cadaba farinose</i> Forssk. | Capparaceae | Bagaye | 1 |
| 9 | <i>Calotropis procera</i> W. T. Aiton | Apocynaceae | Tunfafiya | 3 |
| 10 | <i>Cassia sieberiana</i> DC. | Fabaceae | Malga | 82 |
| 11 | <i>Ceiba pentandra</i> (L.) Gaertn. | Malvaceae | Rini | 1 |
| 12 | <i>Combretum ghasalense</i> Engl. & Diels | Combretaceae | Taramniya | 2 |
| 13 | <i>Combretum micranthum</i> G. Don | Combretaceae | Geza | 71 |
| 14 | <i>Combretum nigricans</i> Lepr. ex Guill. & Perr. | Combretaceae | Tsiriri | 1 |
| 15 | <i>Commiphora africana</i> (A.Rich.) Engl. | Poaceae | Durumi | 1 |
| 16 | <i>Cordia africana</i> Lam. | Fabaceae | Alilliba | 1 |
| 17 | <i>Delonix regia</i> Boj. ex Hook | Fabaceae | Doruwar Turawa | 9 |
| 18 | <i>Detarium microcarpum</i> Guill. & Perr. | Caesalpiniaceae | Taura | 6 |
| 19 | <i>Diospyros mespiliformis</i> Hochst. ex A. DC | Ebenaceae | Kaiwa | 1 |
| 20 | <i>Eucalyptus obliqua</i> L'Hér., Sert. Angl. | Myrtaceae | Zaiti | 2 |
| 21 | <i>Faidherbia albida</i> A.Chev. | Fabaceae | Gawo | 2 |
| 22 | <i>Ficus vallis-choudae</i> Delile | Moraceae | Balgomi | 8 |
| 23 | <i>Gardenia erubescens</i> Stapf & Hutch. | Rubiaceae | Gaude | 3 |
| 24 | <i>Guiera senegalensis</i> J. F. Gmel. | Combretaceae | Sabara | 84 |
| 25 | <i>Khaya senegalensis</i> (Desr.) A. Juss. | Meliaceae | Madacci | 2 |
| 26 | <i>Lannea macrocarpa</i> Engl. & K. Krause | Anacardiaceae | Faru | 20 |
| 27 | <i>Lawsonia inermis</i> Linn. | Rubiaceae | Lalle | 17 |

| | | | | |
|----|---|-----------------|---------|-----|
| 28 | <i>Maerua crassifolia</i> Forssk. | Capparaceae | Jirga | 3 |
| 29 | <i>Mangifera indica</i> Linn. | Anacardiaceae | Mangoro | 17 |
| 30 | <i>Mimosa pigra</i> Linn. | Fabaceae | Gumbi | 51 |
| 31 | <i>Moringa oleifera</i> Lam. | Moringaceae | Zogale | 6 |
| 32 | <i>Parkia biglobosa</i> (Jacq.) Benth | Leguminoseae | Doruwa | 17 |
| 33 | <i>Piliostigma reticulatum</i> (DC.) Hochst. | Caesalpiniaceae | Kalgo | 30 |
| 34 | <i>Prosopis africana</i> (Guill. and Perr.). Taub | Fabaceae | Kiryia | 2 |
| 35 | <i>Psidium guajava</i> Linn. | Myrtaceae | Gwaiba | 11 |
| 36 | <i>Rogeria adenophylla</i> J.Gay ex Delile | Pedaliaceae | Nunu | 11 |
| 37 | <i>Tamarindus indica</i> Linn. | Fabaceae | Tsamiya | 1 |
| 38 | <i>Vitex doniana</i> Sweet | Verbenaceae | Dunya | 11 |
| 39 | <i>Ximenia americana</i> Linn. | Olacaceae | Tsada | 9 |
| 40 | <i>Ziziphus mauritiana</i> Lam. | Rhamnaceae | Magarya | 19 |
| | | | | 671 |

The dominant families identified are Fabaceae, Combretaceae, and Meliaceae. These three families contributed about 66% of the total stems enumerated in the study. On the other hand, many families were represented by few species. Similarly, few species contributed more individuals, while many species were represented by a few individuals (**Table 2**).

3.2. Tree height and diameter

The mean height and mean diameter of species enumerated in the study are presented in **Table 3**. Among the species listed in the table, *Ceiba pentandra* has the highest mean height (24.9 m), followed by *Eucalyptus obliqua* (17.5 m), *Faidherbia albida* (15.1 m), and *Diospyros mespiliiformis* (14.0 m). The least in mean height are *Boscia angustifolia* and *Guiera senegalensis* (5.9 m each) and *Gardenia erubescens* (5.3 m). For most species, mean height did not significantly contribute to total biomass and carbon stocks. For instance, *Eucalyptus obliqua* has a mean height of 17.5 m but contributed only 0.36 kg of carbon. Similarly, *Delonix regia* has a mean height of 12.4 m but contributed only 0.21 kg of carbon (**Table 3**).

3.3. Tree biomass and carbon stock

The total carbon contributed by trees in the area is 120.2 kg, which translates to approximately 0.04 kg/ha. *Azadirachta indica* has the highest net contribution of carbon (53.6 kg), followed by *Cassia sieberiana* (15.1 kg) and *Parkia biglobosa* (7.8 kg). Higher per stem (mean) carbon was, however, contributed by *Combretum ghasalense* (1.23 kg/tree), *Ceiba pentandra* (1.08 kg/tree), *Faidherbia albida* (0.92 kg/tree), and *Prosopis africana* (0.73 kg/tree) (**Table 4**).

Table 2 • Family composition in the area

| S/N | Family | No. of species | No. of stems | % |
|-----|-----------------|----------------|--------------|--------|
| 1 | Anacardiaceae | 2 | 37 | 5.51 |
| 2 | Apocynaceae | 1 | 3 | 0.45 |
| 3 | Balanitaceae | 1 | 21 | 3.13 |
| 4 | Caesalpiniaceae | 2 | 36 | 5.37 |
| 5 | Capparaceae | 2 | 4 | 0.60 |
| 6 | Capparidiaceae | 1 | 12 | 1.79 |
| 7 | Combretaceae | 5 | 159 | 23.70 |
| 8 | Ebenaceae | 1 | 1 | 0.15 |
| 9 | Fabaceae | 10 | 185 | 27.57 |
| 10 | Leguminoseae | 1 | 17 | 2.53 |
| 11 | Malvaceae | 1 | 1 | 0.15 |
| 12 | Meliaceae | 2 | 97 | 14.46 |
| 13 | Moraceae | 1 | 8 | 1.19 |
| 14 | Moringaceae | 1 | 6 | 0.89 |
| 15 | Myrtaceae | 2 | 13 | 1.94 |
| 16 | Olacaceae | 1 | 9 | 1.34 |
| 17 | Pedaliaceae | 1 | 11 | 1.64 |
| 18 | Poaceae | 1 | 1 | 0.15 |
| 19 | Rhamnaceae | 1 | 19 | 2.83 |
| 20 | Rubiaceae | 2 | 20 | 2.98 |
| 21 | Verbenaceae | 1 | 11 | 1.64 |
| | | 40 | 671 | 100.00 |

Table 3 • Mean height and mean diameter of species

| S/N | Species | Family | Mean height (m) | Mean diameter (cm) |
|-----|---|----------------|-----------------|--------------------|
| 1 | <i>Acacia macrostachya</i> Reichenb. ex Benth. | Fabaceae | 6.7 | 7.39 |
| 2 | <i>Acacia nilotica</i> (Linn.) Willd. ex Del. | Fabaceae | 9.4 | 15.09 |
| 3 | <i>Acacia sieberiana</i> var. Woodii | Fabaceae | 7.2 | 7.96 |
| 4 | <i>Anogeissus leiocarpus</i> (DC.) Guill. & Perr. | Combretaceae | 9.6 | 42.97 |
| 5 | <i>Azadirachta indica</i> A. Juss | Meliaceae | 11.4 | 39.89 |
| 6 | <i>Balanites aegyptiaca</i> (Linn.) DeI. | Balanitiaceae | 7.8 | 27.89 |
| 7 | <i>Boscia angustifolia</i> A. Rich. | Capparidiaceae | 5.9 | 13.98 |
| 8 | <i>Cadaba farinose</i> Forssk. | Capparaceae | 9.8 | 25.46 |

| | | | | |
|----|--|---------------|------|-------|
| 9 | <i>Calotropis procera</i> W. T. Aiton | Apocynaceae | 12.0 | 30.66 |
| 10 | <i>Cassia sieberiana</i> DC. | Fabaceae | 9.0 | 25.98 |
| 11 | <i>Ceiba pentandra</i> (L.) Gaertn. | Malvaceae | 24.9 | 83 |
| 12 | <i>Combretum ghasalense</i> Engl. & Diels | Combretaceae | 12.6 | 63.66 |
| 13 | <i>Combretum micranthum</i> G. Don | Combretaceae | 6.6 | 8.13 |
| 14 | <i>Combretum nigricans</i> Lepr. ex Guill. & Perr. | Combretaceae | 11.0 | 41.38 |
| 15 | <i>Commiphora africana</i> (A.Rich.) Engl. | Poaceae | 6.0 | 7.96 |
| 16 | <i>Cordia africana</i> Lam. | Fabaceae | 13.8 | 28.65 |
| 17 | <i>Delonix regia</i> Boj. ex Hook | Fabaceae | 12.4 | 35.30 |
| 18 | <i>Detarium microcarpum</i> Guill. & Perr. | Caesalpiaceae | 9.2 | 30.35 |
| 19 | <i>Diospyros mespiliformis</i> Hochst. ex A. DC | Ebenaceae | 14.0 | 48.38 |
| 20 | <i>Eucalyptus obliqua</i> L'Hér., Sert. Angl. | Myrtaceae | 17.5 | 32.63 |
| 21 | <i>Faidherbia albida</i> A.Chev. | Fabaceae | 15.1 | 65.25 |
| 22 | <i>Ficus vallis-choudae</i> Delile | Moraceae | 7.9 | 13.25 |
| 23 | <i>Gardenia erubescens</i> Stapf & Hutch. | Rubiaceae | 5.3 | 7.00 |
| 24 | <i>Guiera senegalensis</i> J. F. Gmel. | Combretaceae | 5.9 | 6.25 |
| 25 | <i>Khaya senegalensis</i> (Desr.) A. Juss. | Meliaceae | 9.5 | 27.06 |
| 26 | <i>Lannea macrocarpa</i> Engl. & K. Krause | Anacardiaceae | 8.8 | 34.43 |
| 27 | <i>Lawsonia inermis</i> Linn. | Rubiaceae | 6.9 | 5.34 |
| 28 | <i>Maerua crassifolia</i> Forssk. | Capparaceae | 7.9 | 15.28 |
| 29 | <i>Mangifera indica</i> Linn. | Anacardiaceae | 10.2 | 34.90 |
| 30 | <i>Mimosa pigra</i> Linn. | Fabaceae | 8.5 | 8.98 |
| 31 | <i>Moringa oleifera</i> Lam. | Moringaceae | 6.9 | 8.22 |
| 32 | <i>Parkia biglobosa</i> (Jacq.) Benth | Leguminosae | 11.8 | 50.80 |
| 33 | <i>Piliostigma reticulatum</i> (DC.) Hochst. | Caesalpiaceae | 7.6 | 25.53 |
| 34 | <i>Prosopis africana</i> (Guill. and Perr.) Taub | Fabaceae | 10.8 | 47.75 |
| 35 | <i>Psidium guajava</i> Linn. | Myrtaceae | 6.3 | 8.68 |
| 36 | <i>Rogeria adenophylla</i> J. Gay ex Delile | Pedaliaceae | 7.5 | 22.14 |
| 37 | <i>Tamarindus indica</i> Linn. | Fabaceae | 8.5 | 38.2 |
| 38 | <i>Vitex doniana</i> Sweet | Verbenaceae | 6.8 | 28.07 |
| 39 | <i>Ximenia americana</i> Linn. | Olacaceae | 6.2 | 8.35 |
| 40 | <i>Ziziphus mauritiana</i> Lam. | Rhamnaceae | 7.7 | 19.22 |

Table 4 • Total biomass and carbon stock of species

| S/N | Species | Family | ρ (g/cm ³) | No | Total | | Mean | |
|-----|------------------------------|----------------|-----------------------------|----|--------|--------|--------|--------|
| | | | | | Y (kg) | C (kg) | Y (kg) | C (kg) |
| 1 | <i>Acacia macrostachya</i> | Fabaceae | 0.74 | 24 | 0.63 | 0.31 | 0.026 | 0.013 |
| 2 | <i>Acacia nilotica</i> | Fabaceae | 0.76 | 5 | 0.44 | 0.22 | 0.088 | 0.044 |
| 3 | <i>Acacia sieberiana</i> | Fabaceae | 0.72 | 8 | 0.17 | 0.08 | 0.021 | 0.011 |
| 4 | <i>Anogeissus leiocarpus</i> | Combretaceae | 0.96 | 1 | 0.85 | 0.42 | 0.85 | 0.42 |
| 5 | <i>Azadirachta indica</i> | Meliaceae | 0.77 | 95 | 107.12 | 53.56 | 1.13 | 0.56 |
| 6 | <i>Balanites aegyptiaca</i> | Balanitiaceae | 0.78 | 21 | 6.49 | 3.25 | 0.31 | 0.15 |
| 7 | <i>Boscia angustifolia</i> | Capparidiaceae | 0.44 | 12 | 0.39 | 0.20 | 0.033 | 0.02 |
| 8 | <i>Cadaba farinosa</i> | Capparaceae | * | 1 | 0.00 | 0.00 | 0.00 | 0.00 |
| 9 | <i>Calotropis procera</i> | Apocynaceae | * | 3 | 0.00 | 0.00 | 0.00 | 0.00 |
| 10 | <i>Cassia sieberiana</i> | Fabaceae | 0.74 | 82 | 30.12 | 15.06 | 0.37 | 0.18 |
| 11 | <i>Ceiba pentandra</i> | Malvaceae | 0.26 | 1 | 2.15 | 1.08 | 2.15 | 1.08 |
| 12 | <i>Combretum ghasalense</i> | Combretaceae | 0.96 | 2 | 4.94 | 2.47 | 2.47 | 1.23 |
| 13 | <i>Combretum micranthum</i> | Combretaceae | 0.76 | 71 | 11.51 | 5.75 | 0.162 | 0.08 |
| 14 | <i>Combretum nigricans</i> | Combretaceae | 0.75 | 1 | 0.70 | 0.35 | 0.70 | 0.35 |
| 15 | <i>Commiphora africana</i> | Poaceae | 0.28 | 1 | 0.01 | 0.00 | 0.01 | 0.003 |
| 16 | <i>Cordia africana</i> | Fabaceae | 0.48 | 1 | 0.28 | 0.14 | 0.28 | 0.14 |

| | | | | | | | | |
|----|--------------------------------|-----------------|------|-----|--------|--------|-------|-------|
| 17 | <i>Delonix regia</i> | Fabaceae | 0.51 | 9 | 3.79 | 1.89 | 0.42 | 0.21 |
| 18 | <i>Detarium microcarpum</i> | Caesalpiniaceae | 0.56 | 6 | 1.89 | 0.94 | 0.31 | 0.16 |
| 19 | <i>Diospyros mespiliformis</i> | Ebenaceae | 0.77 | 1 | 1.24 | 0.62 | 1.24 | 0.62 |
| 20 | <i>Eucalyptus obliqua</i> | Myrtaceae | 0.72 | 2 | 1.44 | 0.72 | 0.72 | 0.36 |
| 21 | <i>Faidherbia albida</i> | Fabaceae | 0.58 | 2 | 3.66 | 1.83 | 1.83 | 0.92 |
| 22 | <i>Ficus vallis-choudae</i> | Moraceae | 0.32 | 8 | 0.31 | 0.15 | 0.04 | 0.02 |
| 23 | <i>Gardenia erubescens</i> | Rubiaceae | 0.64 | 3 | 0.03 | 0.02 | 0.011 | 0.01 |
| 24 | <i>Guiera senegalensis</i> | Combretaceae | 0.66 | 84 | 1.00 | 0.50 | 0.01 | 0.01 |
| 25 | <i>Khaya senegalensis</i> | Meliaceae | 0.69 | 2 | 0.53 | 0.27 | 0.27 | 0.13 |
| 26 | <i>Lannea microcarpa</i> | Anacardiaceae | 0.39 | 20 | 5.86 | 2.93 | 0.29 | 0.15 |
| 27 | <i>Lawsonia inermis</i> | Rubiaceae | * | 17 | 0.00 | 0.00 | 0.00 | 0.001 |
| 28 | <i>Maerua crassifolia</i> | Capparaceae | 0.57 | 3 | 0.12 | 0.06 | 0.04 | 0.02 |
| 29 | <i>Mangifera indica</i> | Anacardiaceae | 0.55 | 17 | 9.53 | 4.77 | 0.56 | 0.28 |
| 30 | <i>Mimosa pigra</i> | Fabaceae | 0.73 | 51 | 3.39 | 1.69 | 0.07 | 0.033 |
| 31 | <i>Moringa oleifera</i> | Moringaceae | 0.27 | 6 | 0.05 | 0.02 | 0.01 | 0.004 |
| 32 | <i>Parkia biglobosa</i> | Leguminosae | 0.53 | 17 | 15.51 | 7.76 | 0.91 | 0.46 |
| 33 | <i>Piliostigma reticulatum</i> | Caesalpiniaceae | 0.67 | 30 | 8.98 | 4.49 | 0.30 | 0.15 |
| 34 | <i>Prosopis africana</i> | Fabaceae | 0.84 | 2 | 2.93 | 1.47 | 1.47 | 0.73 |
| 35 | <i>Psidium guajava</i> | Myrtaceae | 0.63 | 11 | 0.20 | 0.10 | 0.02 | 0.01 |
| 36 | <i>Rogeria adenophylla</i> | Pedaliaceae | 0.54 | 11 | 1.62 | 0.81 | 0.15 | 0.07 |
| 37 | <i>Tamarindus indica</i> | Fabaceae | 0.73 | 1 | 0.46 | 0.23 | 0.46 | 0.23 |
| 38 | <i>Vitex doniana</i> | Verbenaceae | 0.45 | 11 | 2.92 | 1.46 | 0.27 | 0.13 |
| 39 | <i>Ximenia americana</i> | Olacaceae | 0.95 | 9 | 0.23 | 0.11 | 0.03 | 0.013 |
| 40 | <i>Ziziphus abyssiniaca</i> | Rhamnaceae | 0.74 | 19 | 8.93 | 4.47 | 0.47 | 0.24 |
| | | | | 671 | 240.42 | 120.21 | | |

*Wood density (ρ) for the species could not be obtained, and hence were not considered for analysis of aboveground biomass and carbon. Y, Biomass; C, Carbon Stock.

4. Discussion

Most of the species (ten) were in the family Fabaceae, notably *Acacia macrostachya*, *Acacia nilotica*, *Cassia sieberiana*, *Delonix regia*, and *Faidherbia albida*. This family has 185 stems and accounted for 27.6% of the total stems enumerated. This was followed by the family Combretaceae, which has five species including *Anogeissus leiocarpus*, *Combretum micranthum*, *Combretum ghasalense*, *Combretum nigricans*, and *Guiera senegalensis*. These species contributed 159 stems, accounting for 23.7% of the total stems. The families with fewer species and tree stems include Ebenaceae, Malvaceae, and Poaceae. Each of these has only one species, contributing just about 0.2% of the total stems.

Most of the trees enumerated in this study have small to medium diameter. *Ceiba pentandra*, which has the highest mean height, also has the highest mean diameter (83 cm). Other species with high mean diameter include *Faidherbia albida* (65.3 cm), *Combretum ghasalense* (63.7 cm), *Parkia biglobosa* (50.8 cm), *Diospyros mespiliformis* (48.4 cm), and *Prosopis africana* (47.8 cm). On the other hand, species with the least mean diameter are *Gardenia erubescens* (7.0 cm), *Guiera senegalensis* (6.3 cm), and *Lawsonia inermis* (5.3 cm). Analysis of the species diameter shows that small-diameter trees (<10–15 cm) comprise 57.1% of the total species, medium-diameter trees (15–40 cm) comprise 26.7%, and large-diameter trees (>40 cm) comprise 16.2%. The higher percentage of small-diameter trees recorded in this study may be due to overharvesting and unsustainable utilization of comparatively larger-diameter trees for fuelwood and other purposes, which significantly affects tree species population structure [53].

The diameter class distribution showed a reversed J curve (**Figure 3**) which is typical of diameter distribution in many studies [78–81]. According to Peterson [82] and Gebeyehu [83], this suggests a stable and expanding tree species population structure, with tree density traditionally declining with increasing diameter [81]. Hence, small-diameter trees account for the larger percentage of the stems due to continuous recruitment in a sustainable system, while large-diameter stems account for a smaller percentage [53, 84].

Except for *Azadirachta indica*, all the species that contributed to higher biomass and carbon are native to the area. This tallies with a number of studies [5, 43, 85, 86], where native tree species were shown to have high potentials for storing considerable amounts of biomass and carbon stock especially in dry and semi-arid climates [19, 87]. Moderate mean biomass and corresponding carbon stock were observed on *Diospyros mespiliformis* ($Y = 1.24$ kg/tree, $C = 0.62$ kg/tree), *Azadirachta indica* ($Y = 1.13$ kg/tree, $C = 0.56$ kg/tree), *Parkia biglobosa* ($Y = 1.14$ kg/tree, $C = 0.46$ kg/tree), and *Anogeissus leiocarpus* ($Y = 0.85$ kg/tree, $C = 0.42$ kg/tree). Other species such as *Commiphora africana*, *Gardenia erubescens*, *Moringa oleifera*, and *Ximenia americana* contributed infinitesimally to the biomass and carbon stock of the area (**Table 4**).

The carbon accumulated by trees in this area is considerably low, especially compared to findings from similar areas. For instance, McNicol et al. [12] found an overall landscape average of 24 ± 16 t/ha in southeastern Tanzania. Furthermore, Moussa et al. [46] also found mean carbon stock to be 31.63 t/ha in Niamey and 58.30 t/ha in Maradi, while Mensah et al. [19] found an average

carbon storage of 42 mg per hectare in the Bellefougou Forest Reserve. However, this may be due to the presence of many large-diameter trees which accounted for much of the carbon in the area. From the above, it could be deduced that the absence of large-diameter trees in the current study area has led to a considerably low per hectare stock of carbon.

As found in a number of recent studies [12, 19, 22, 46], much of the carbon stocks in Africa are stored by medium- to large-diameter trees. In this study also, large-diameter trees were found to store most of the biomass and carbon, but as opined by [31], this does not underscore the contribution of smaller-diameter trees

in the total carbon of the area. In many forest stands, small-diameter trees form a considerable percentage of the total trees. For instance, they constituted 93.6% in Rabi Forest, Gabon [47], 81.6% in Kilwa District in the Lindi Region of southeastern Tanzania [12], 60.5% in the wet tropical rainforests of Australia [45], and 60% in the Mahendragiri Hill, India [38], among others. Hence, small and medium trees are also important in predicting and contributing to the AGB and carbon stock of an area [19]. This is more so as the trees grow, accumulating biomass and carbon stocks over time.

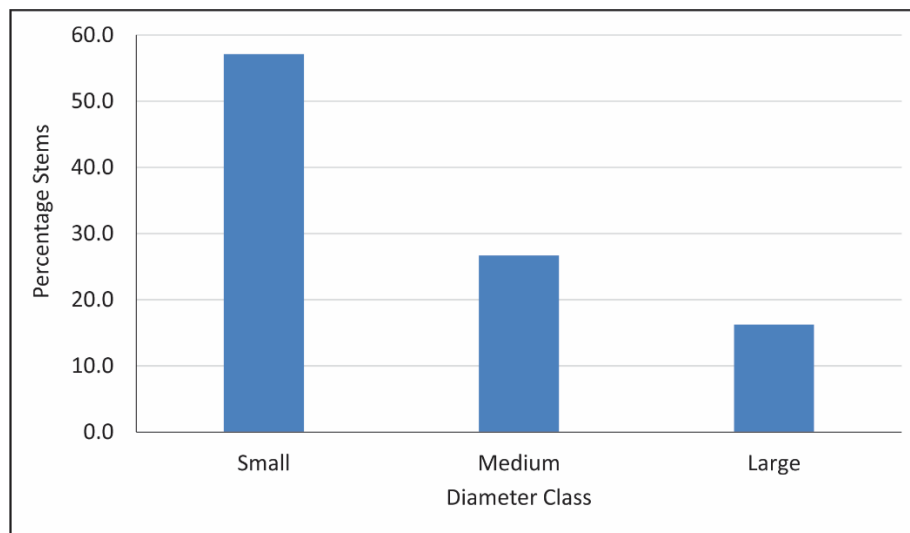


Figure 3 • Diameter class distribution.

5. Conclusions

This study evaluated the contribution of small- and medium-diameter trees in the regional carbon pool of West African savanna, using an allometric equation. The study confirms that larger-diameter trees account for much of biomass and carbon stock in a given area. However, this does not underscore the importance and contribution of small- and medium-diameter trees in carbon storage especially in dry environments where they form a greater percentage of available trees. Measures should, therefore, be taken to conserve these trees to ensure sustainability of forests especially in dry environments.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Data supporting these findings are available within the article, at <https://doi.org/10.20935/AcadEnvSci7473>, or upon request.

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References

- World Meteorological Organization. The state of greenhouse gases in the atmosphere based on global observations through 2013. 2014 [cited 2024 June 1]. Available from: <https://library.wmo.int/records/item/58544-no-10-9-september-2014-climate-summit-edition>
- Lasco RD, MacDicken KG, Pulhin FB, Guillermo IQ, Sales RF, Cruz RVO. Carbon stocks assessment of a selectively logged dipterocarp forest and wood processing mill in the Philippines. *J Trop For Sci.* 2006;18(4):212–21.
- Grace J. Understanding and managing the global carbon cycle. *Jo Ecol.* 2004;92(2):189–202. doi: 10.1111/j.0022-0477.2004.00874.x
- Nowak DJ, Crane DE. Carbon storage and sequestration by urban trees in the USA. *Environ Pollut.* 2002;116(3):381–9. doi: 10.1016/S0269-7491(01)00214-7
- Zubair M, Yasin J, Qazlbash SK, Ul Haq A, Jamil A, Yaseen M, et al. Carbon sequestration by native tree species around the industrial areas of southern Punjab, Pakistan. *Land.* 2022;11(9):1–12. doi: 10.3390/land11091577
- Bakkes JA, Bosch PR, Bouwman AF, Eerens HC, Elzen MG, Janssen PHM, et al. Background report to the OECD environmental outlook to 2030 overviews, details, and methodology of model-based analysis. 2008 [cited 2024 June 1]. Available from: <https://www.pbl.nl/en/publications/background-report-to-the-oecd-environmental-outlook-to-2030>
- Ding ZL, Duan XN, Ge QS, Zhang ZQ. Control of atmospheric CO₂ concentrations by 2050: a calculation on the emission rights of different countries. *Sci China Ser D Earth Sci.* 2009;52(10):1447–69. doi: 10.1007/s11430-009-0155-3
- Weber JC, Montes CS, Abasse TA, Sanquetta C. Variation in growth, wood density and carbon concentration in five tree and shrub species in Niger. *New For.* 2018;49:35–51. doi: 10.1007/s11056-017-9603-7
- Shackleton CM, Scholes RJ. Above ground woody community attributes, biomass and carbon stocks along a rainfall gradient in the savannas of the central lowveld, South Africa. *S Afr J Bot.* 2011;77(1):184–92. doi: 10.1016/J.SAJB.2010.07.014
- Osborne CP, Charles-Dominique T, Stevens N, Bond WJ, Midgley G, Lehmann CER. Human impacts in African savannas are mediated by plant functional traits. *New Phytol.* 2018;220(1):10–24. doi: 10.1111/NPH.15236
- Chapungu L, Nhamo L, Gatti RC. Estimating biomass of savanna grasslands as a proxy of carbon stock using multispectral remote sensing. *Remote Sens Appl.* 2020;17:100275. doi: 10.1016/J.RSASE.2019.100275
- McNicol IM, Ryan CM, Dexter KG, Ball SMJ, Williams M. Aboveground carbon storage and its links to stand structure, tree diversity and floristic composition in south-eastern Tanzania. *Ecosystems.* 2018;21(4):740–54. doi: 10.1007/s10021-017-0180-6
- Ross CW, Hanan NP, Prihodko L, Anchang J, Ji W, Yu Q. Woody-biomass projections and drivers of change in sub-Saharan Africa. *Nat Clim Chang.* 2021;11(5):449–55. doi: 10.1038/s41558-021-01034-5
- Tucker C, et al. Sub-continental-scale carbon stocks of individual trees in African drylands. *Nature.* 2023;615(7950):80–6. doi: 10.1038/s41586-022-05653-6
- Dimobe K, Tondoh JE, Weber JC, Bayala J, Ouedraogo K, Greenough K. Farmers' preferred tree species and their potential carbon stocks in southern Burkina Faso: implications for biocarbon initiatives. *PLoS One.* 2018;13(12):e0199488. doi: 10.1371/journal.pone.0199488
- Ouédraogo S, Ouédraogo O, Dimobe K, Thiombiano A, Bous-sim JI. Prediction of aboveground biomass and carbon stock of *Balanites aegyptaca*, a multipurpose species in Burkina Faso. *Heliyon.* 2020;6(8):e04581. doi: 10.1016/j.heliyon.2020.e04581
- Hasen-Yusuf M, Treydte AC, Abule E, Sauerborn J. Predicting aboveground biomass of woody encroacher species in semi-arid rangelands, Ethiopia. *J Arid Environ.* 2013;96:64–72. doi: 10.1016/j.jaridenv.2013.04.007
- Ganamé M, Bayen P, Dimobe K, Ouédraogo I, Thiombiano A. Aboveground biomass allocation, additive biomass and carbon sequestration models for *Pterocarpus erinaceus* Poir. in Burkina Faso. *Heliyon.* 2020;6(4):e03805. doi: 10.1016/J.HELIYON.2020.E03805
- Mensah S, Noulèkoun F, Ago EE. Aboveground tree carbon stocks in West African semi-arid ecosystems: dominance patterns, size class allocation and structural drivers. *Glob Ecol Conserv.* 2020;24:e01331. doi: 10.1016/j.gecco.2020.e01331
- Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti, WBC, et al. Improved allometric models to estimate the aboveground biomass of tropical trees. *Glob Chang Biol.* 2014;20(10):3177–90. doi: 10.1111/gcb.12629
- Dangulla M, Abd Manaf L, Ramli MF, Yacob R. Urban tree composition, diversity and structural characteristics in

- North-western Nigeria. Urban for Urban Green. 2020;48:126512, doi: 10.1016/j.ufug.2019.126512
22. Dangulla M, Abd Manaf L, Ramli MF, Yacob MR, Namadi S. Exploring urban tree diversity and carbon stocks in Zaria Metropolis, North Western Nigeria. Appl Geogr. 2021;127:102385. doi: 10.1016/j.apgeog.2021.102385
 23. McPherson EG, van Doorn N, de Goede J. Structure, function and value of street trees in California, USA. Urban For Urban Green. 2016;17:104–15. doi: 10.1016/j.ufug.2016.03.013
 24. Wang B, et al. Carbon pools in forest systems and new estimation based on an investigation of carbon sequestration. J Environ Manage. 2024;360:121124. doi: 10.1016/J.JENVMAN.2024.121124
 25. Nguyen TD, Kappas M. Estimating the aboveground biomass of an evergreen broadleaf forest in Xuan Lien Nature Reserve, Thanh Hoa, Vietnam, using SPOT-6 data and the random forest algorithm. Int J For Res. 2020;2020:4216160. doi: 10.1155/2020/4216160
 26. Ouédraogo K, Dimobe K, Thiombiano A. Allometric models for estimating aboveground biomass and carbon stock for *Diospyros mespiliiformis* in West Africa. Silva Fennica. 2020; 54(1):10215. doi: 10.14214/sf.10215
 27. Mukuralinda A, Kuyah S, Ruzibiza M, Ndoli A, Nabahungu NL, Muthuri C. Allometric equations, wood density and partitioning of aboveground biomass in the arboretum of Ruhande, Rwanda. Trees For People. 2021;3:100050. doi: 10.1016/J.TFP.2020.100050
 28. Djomo AN, Chimi CD. Tree allometric equations for estimation of above, below and total biomass in a tropical moist forest: Case study with application to remote sensing. For Ecol Manage. 2017;391:184–93. doi: 10.1016/j.foreco.2017.02.022
 29. Nogueira FCB, Dobe EK, Silva Filho JB, Rodrigues LS. Allometric equations to estimate aboveground biomass of *Dalbergia cearensis* species in the Brazilian seasonally dry tropical forest. For Ecol Manage. 2021;484:118920. doi: 10.1016/j.foreco.2021.118920
 30. Kankare V, Holopainen M, Vastaranta M, Puttonen E, Yu X, Hyypä J, et al. Individual tree biomass estimation using terrestrial laser scanning. ISPRS J Photogramm Remote Sens. 2013;75: 64–75. doi: 10.1016/j.isprsjprs.2012.10.003
 31. Baishya R, Kanta Barik S, Upadhaya K. Distribution pattern of aboveground biomass in natural and plantation forests of humid tropics in northeast India. Trop Ecol. 2009;50(2): 295–304.
 32. Aabeyir R, Adu-Bredu S, Agyare WA, Weir MJC. Allometric models for estimating aboveground biomass in the tropical woodlands of Ghana, West Africa. For Ecosyst. 2020;7(1):1–23. doi: 10.1186/S40663-020-00250-3
 33. Henry M, et al. Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. Silva Fennica. 2011;45(3B):477–569. doi: 10.14214/sf.38
 34. Abich A, Alemu A, Gebremariam Y, Mucheye T, Gurebiyaw K, Kassie M. Allometric models for predicting aboveground biomass of Combretum-Terminalia woodlands in Amhara, Northwest Ethiopia. Trees, Forests and People. 2021;5: 100122. doi: 10.1016/J.TFP.2021.100122
 35. Liu C, Li X. Carbon storage and sequestration by urban forests in Shenyang, China. Urban For Urban Green. 2012;11(2):121–8. doi: 10.1016/j.ufug.2011.03.002
 36. Zhao H, Li Z, Zhou G, Qiu Z, Wu Z. Site-specific allometric models for prediction of above-and belowground biomass of subtropical forests in Guangzhou, Southern China. Forests. 2019;10(10):1–16. doi: 10.3390/f10100862
 37. Mugabowindekwe M, Brandt M, Chave J, Reiner F, Skole DL, Kariryaa A, et al. Nation-wide mapping of tree-level above-ground carbon stocks in Rwanda. Nat Clim Chang. 2023; 13(1):91–7. doi: 10.1038/s41558-022-01544-w
 38. Khadanga SS, Jayakumar S. Tree biomass and carbon stock: understanding the role of species richness, elevation, and disturbance. Trop Ecol. 2020;61(1):128–41. doi: 10.1007/s42965-020-00070-0
 39. Escobedo F, Seitz JA, Zipperer W. Carbon sequestration and storage by Gainesville's urban forest. FOR210. 2009 [cited 2024 June 1]. Available from: https://www.srs.fs.usda.gov/pubs/ja/ja_zipperer004.pdf
 40. Meena A, Bidalia A, Hanief M, Dinakaran J, Rao KS. Assessment of above- and belowground carbon pools in a semi-arid forest ecosystem of Delhi, India. Ecol Process. 2019;8:8. doi: 10.1186/s13717-019-0163-y
 41. Mildrexler DJ, Berner LT, Law BE, Birdsey RA, Moomaw WR, Dean TJ. Large trees dominate carbon storage in forests east of the cascade crest in the United States Pacific Northwest. Front For Glob Change. 2020;3:1–15. doi: 10.3389/ffgc.2020.594274
 42. Lutz JA, Struckman S, Germain SJ, Furniss TJ. The importance of large-diameter trees to the creation of snag and deadwood biomass. Ecol Process. 2021;10(1):28. doi: 10.1186/s13717-021-00299-0
 43. Stoffberg GH, van Rooyen MW, van der Linde MJ, Groeneveld HT. Carbon sequestration estimates of indigenous street trees in the City of Tshwane, South Africa. Urban For Urban Green. 2010;9(1):9–14. doi: 10.1016/j.ufug.2009.09.004
 44. Amoatey P, Sulaiman H. Quantifying carbon storage potential of urban plantations and landscapes in Muscat, Oman. Environ Dev Sustain. 2020;22(8):7969–84. doi: 10.1007/s10668-019-00556-5
 45. Bradford M, Murphy HT. The importance of large-diameter trees in the wet tropical rainforests of Australia. PLoS One. 2019;14(5):e0208377. doi: 10.1371/JOURNAL.PONE.0208377
 46. Moussa S, Kyereh B, Tougiani A, Kuyah S, Saadou M. West African Sahelian cities as source of carbon stocks: Evidence from Niger. Sustain Cities Soc. 2019;50:101653. doi: 10.1016/j.scs.2019.101653
 47. Memiaghe HR, Lutz JA, Korte L, Alonso A, Kenfack D. Ecological importance of small-diameter trees to the structure, diversity and biomass of a tropical evergreen forest at Rabi, Gabon. PLoS One. 2016;11(5):e0154988. doi: 10.1371/journal.pone.0154988
 48. Nicholson SE. The West African Sahel: a review of recent studies on the rainfall regime and its interannual variability. ISRN Meteorol. 2013;2013:1–32. doi: 10.1155/2013/453521

49. Karlson M, Ostwald M. Remote sensing of vegetation in the Sudano-Sahelian zone: a literature review from 1975 to 2014. *J Arid Environ.* 2016;124:257–69. doi: 10.1016/J.JARIDENV.2015.08.022
50. Brandt M, Tucker CJ, Kariryaa A, Rasmussen K, Abel C, Small J, et al. An unexpectedly large count of trees in the West African Sahara and Sahel. *Nature.* 2020;587(7832):78–82. doi: 10.1038/s41586-020-2824-5
51. Hutchinson J, Dalziel JM. *Flora of West Tropical Africa*, Revised, no. December. London: Crown Agents for Overseas Governments and Administrations; 1972.
52. Kershaw JA, Ducey MJ, Beers TW, Husch B. *Forest mensuration*. 5th ed. Chichester: John Wiley & Sons; 2016.
53. Jew EKK, Dougill AJ, Sallu SM, O’Connell J, Benton TG. Miombo woodland under threat: consequences for tree diversity and carbon storage. *For Ecol Manage.* 2016;361:144–53. doi: 10.1016/j.foreco.2015.11.011
54. Nölke N, Fehrmann L, Jaya INS, Tiryana T, Seidel D, Kleinn C. On the geometry and allometry of big-buttressed trees - a challenge for forest monitoring: new insights from 3D-modeling with terrestrial laser scanning. *IForest.* 2015;8(5):574. doi: 10.3832/IFOR1449-007
55. Rutishauser E, Noor’an F, Laumonier Y, Halperin J, Rufi’ie, Hergoualc K, et al. Generic allometric models including height best estimate forest biomass and carbon stocks in Indonesia. *For Ecol Manage.* 2013;307(2013):219–25. doi: 10.1016/j.foreco.2013.07.013
56. Brown S, Gillespie AJR, Lugo AE. Biomass estimation methods for tropical forests with applications to forest inventory data. *For Sci.* 1989;35(4):881–902. doi: 10.1093/forest-science/35.4.881
57. Brown S. *Estimating biomass and biomass change of tropical forests: a primer*. Rome: Food and Agriculture Organization of the United Nations; 1997. p. 134. ISBN 92-5-103955-0.
58. Feldpausch TR, Lloyd J, Lewis SL, Brienen RJW, Gloor M, Mendoza AM, et al. Tree height integrated into pantropical forest biomass estimates. *Biogeosciences.* 2012;9:3381–403. doi: 10.5194/bg-9-3381-2012
59. Feldpausch TR, Banin L, Phillips OL, Baker TR, Lewis SL, Quesada CA. Height-diameter allometry of tropical forest trees. *Biogeosciences.* 2011;8:1081–106. doi: 10.5194/bg-8-1081-2011
60. Pellikka PKE, Heikinheimo V, Hietanen J, Schäfer E, Siljander M, Heiskanen J. Impact of land cover change on aboveground carbon stocks in Afri-montane landscape in Kenya. *Appl Geogr.* 2018;94:178–89. doi: 10.1016/j.apgeog.2018.03.017
61. Solomon N, Pabi O, Annang T, Asante IK, Birhane E. The effects of land cover change on carbon stock dynamics in a dry Afri-montane forest in northern Ethiopia. *Carbon Balance Manag.* 2018;13(14):1–13. doi: 10.1186/s13021-018-0103-7
62. Mokany K, Raison RJ, Prokushkin AS. Critical analysis of root: shoot ratios in terrestrial biomes. *Glob Chang Biol.* 2006;12(1):84–96. doi: 10.1111/j.1365-2486.2005.001043.x
63. Ekoungoulou R, Nzala D, Liu X, Niu S. Tree biomass estimation in central African forests using allometric models. *Open J Ecol.* 2018;08(03):209–37. doi: 10.4236/oje.2018.83014
64. Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE. Towards a worldwide wood economics spectrum. *Ecol Lett.* 2009;12(4):351–66. doi: 10.1111/j.1461-0248.2009.01285.x
65. Orwa C, Mutua A, Kindt R, Jamnadass R, Simons A. *Agroforestry database: a tree reference and selection guide version 4.0*. World Agroforestry Centre, Kenya; 2009 [cited 2024 June 1]. Available from: <https://www.worldagroforestry.org/output/agroforestry-database>
66. Hasmadi MI, Zaki PH, Hamed HA. Wood density and carbon estimates of mangrove species in Kuala Sepetang, Perak, Malaysia. *Malaysian For.* 2015;78(1 & 2):115–24.
67. Nowak DJ, Greenfield EJ, Hoehn RE, Lapoint E. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environ Pollut.* 2013;178:229–36. doi: 10.1016/j.envpol.2013.03.019
68. IPCC. *Guidelines for national greenhouse gas inventories*. Vol. 4. Geneva: IPCC; 2006.
69. Tang Y, Chen A, Zhao S. Carbon storage and sequestration of urban street trees in Beijing, China. *Front Ecol Evol.* 2016;4(53):1–8. doi: 10.3389/fevo.2016.00053
70. Rieger I, Kowarik I, Cierjacks A, Pan Y. Drivers of carbon sequestration by biomass compartment of Riparian forests. *Ecosphere.* 2015;6(10):1–16. doi: 10.1890/ES14-00330.1
71. Chisanga K, Bhardwaj DR, Pala NA, Thakur CL. Biomass production and carbon stock inventory of high-altitude dry temperate land use systems in North Western Himalaya. *Ecol Process.* 2018;2(22):1–13. doi: 10.1186/s13717-018-0134-8
72. Smith JE, Heath LS, Hoover CM. Carbon factors and models for forest carbon estimates for the 2005-2011 National Greenhouse Gas Inventories of the United States. *For Ecol Manage.* 2013;307:7–19. doi: 10.1016/j.foreco.2013.06.061
73. Rahman MDM, Nabiul M, Khan I, Fazlul Hoque AK, Ahmed I. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. *Wetl Ecol Manag.* 2015;23:269–83. doi: 10.1007/s11273-014-9379-x
74. Morhart C, Sheppard JP, Schuler JK, Spiecker H. Above-ground woody biomass allocation and within tree carbon and nutrient distribution of wild cherry (*Prunus avium* L.) – a case study. *For Ecosyst.* 2016;3(4):1–15. doi: 10.1186/s40663-016-0063-x
75. Salas Macías CA, Alegre Orihuela JC, Iglesias Abad S. Estimation of above-ground live biomass and carbon stocks in different plant formations and in the soil of dry forests of the Ecuadorian coast. *Food Energy Secur.* 2017;1(e115):1–7. doi: 10.1002/fes3.115
76. Tashi S, Singh B, Keitel C, Adams M. Soil carbon and nitrogen stocks in forests along an altitudinal gradient in the eastern Himalayas and a meta-analysis of global data. *Glob Chang Biol.* 2016;22:2255–68. doi: 10.1111/gcb.13234

77. Atawodi SE, Atawodi JC. *Azadirachta indica* (neem): a plant of multiple biological and pharmacological activities. *Phytochem Rev.* 2009;8:601–20. doi: 10.1007/s11101-009-9144-6
78. Li Y, He J, Yu S, Wang H, Ye S. Spatial structures of different-sized tree species in a secondary forest in the early succession stage. *Eur J For Res.* 2020;139(5):709–19. doi: 10.1007/s10342-020-01280-w
79. Gao Y, Li L, Du X, Meng J. A transition-matrix growth model and equilibrium curve for natural forests in Jiangxi Province. *Forests.* 2023;14(10):2038. doi: 10.3390/f14102038
80. Zhang M, Wang J, Kang X. Spatial distribution pattern of dominant tree species in different disturbance plots in the Changbai Mountain. *Sci Rep.* 2022;12(1):1–12. doi: 10.1038/s41598-022-18621-x
81. Mensah S, Egeru A, Assogbadjo AE, Glèlè Kakaï R. Vegetation structure, dominance patterns and height growth in an Afromontane forest, Southern Africa. *J For Res.* 2020;31(2):453–62. doi: 10.1007/s11676-018-0801-8
82. Peterson CM. Sustainable harvest of non-timber plant resources in tropical moist forest: an ecological primer. Washington (DC): Biodiversity Support Program; 1999.
83. Gebeyehu G, Soromessa T, Bekele T, Teketay D. Species composition, stand structure, and regeneration status of tree species in dry Afromontane forests of Awi Zone, northwestern Ethiopia. *Ecosyst Health Sust.* 2019;5(1):199–215. doi: 10.1080/20964129.2019.1664938
84. Hörnberg G, Ohlson M, Zackrisson O. Stand dynamics, regeneration patterns and long-term continuity in boreal old-growth *Picea abies* swamp-forests. *J Veg Sci.* 1995;6(2):291–8. doi: 10.2307/3236224
85. Thomas SC, Malczewski G, Sapruff M. Assessing the potential of native tree species for carbon sequestration forestry in Northeast China. *J Environ Manage.* 2007;85(3):663–71. doi: 10.1016/j.jenvman.2006.04.027
86. Omoro LM, Starr M, Pellikka PK, Lma O, Pke P. Tree biomass and soil carbon stocks in indigenous forests in comparison to plantations of exotic species in the Taita Hills of Kenya. *Silva Fennica.* 2013;47(2):1–18. doi: 10.14214/sf.935
87. Lázaro-Lobo A, Ruiz-Benito P, Cruz-Alonso V, Castro-Díez P. Quantifying carbon storage and sequestration by native and non-native forests under contrasting climate types. *Glob Chang Biol.* 2023;29(16):4530–42. doi: 10.1111/gcb.16810