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Modeling Carbon Stock-Dendrometric Parameters Relationship and Tree Species Diversity in Abu-Gadaf Natural Forest Reserve, Sudan

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ABSTRACT

This study modeled the relationships between aboveground carbon stock and tree densitometric parameters (diameter and height) as well as the species diversity in Abu-Gadaf Natural Forest Reserve, Sudan. Forty-six sample plots were systematically inventoried across the low and highland areas of the reserve, and tree diameter at breast height, total height, density, and regeneration trends were measured. The Shannon, evenness, and richness indices were assessed using the recommended equations and the polynomial regression for carbon stock-dendrometric parameters modeling. The study findings illustrated that highland areas have high species richness, evenness, and Shannon index value with 45 tree species and excellent regeneration for dominant tree species. However, the lowlands accommodate 30 tree species with low tree density and aboveground biomass. Moreover, the carbon stock-tree diameter relationship exhibited a strong polynomial correlation with R2 value of 0.93 in comparison to carbon stock-tree height ones. While the reserve hosts a considerable number of tree species, particularly in the highland areas, several none regenerated species in the lowland sites need a quick intervention for further conservation. Accordingly, the participatory approach of community forestry can successfully guide the restoration plan of the influenced areas across the reserve.

Keywords: Carbon Stock, Forest, Regeneration, Species Diversity, Tree Density, Tree Diameter

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1. INTRODUCTION

Natural forest reserves contribute significantly to the mitigation of climate change (Bai et al. 2022), rural community development (Khamis and Abdalla, 2017), and locals' livelihood satisfaction (Suleiman et al. 2017). They clean the atmosphere by absorbing CO_2 and releasing O_2 as a byproduct of the photosynthesis process (Ibrahim et al. 2018). The protected forest sites store about 115 Mg/ha of carbon within aboveground biomass Worldwide (Dimobe et al. 2019) and 82.8 Mg/ha in the African continent (Dimobe et al. 2019). However, under the rapid human population growth, increasing consumption, and intensive pressure on forest resources, more CO_2 can be released, and more forested lands will be lost.

Though carbon stock can vary between aboveground and underground biomass based on plant type, plant organs, and elevation, exploring the correlations between tree species diversity and carbon storage aboveground can support the sustainable management of forest resources and accelerate the reduction of CO_2, particularly for low-income countries like Sudan. Sudan as a Sub-Saharan African country characterized by a dry climate in the north and a wet and rainy one in the south with rich biodiversity commonly found across the country riverine, urban, natural, institutional, community, private forests, and biosphere reserves (Hassan et al. 2022; Ibrahim et al. 2018; Tahir and Yousif, 2013). While several studies have addressed the effects of anthropogenic activities and climatic variability on forest population dynamics, species diversity, forest composition, soil fertility, and wild animal species (Hasoba et al. 2020; Hassaballah et al. 2020; Mohammed, Elhag, et al. 2021), few were concerned with species diversity and carbon storage. This study fills this gap and models the relationship between carbon storage and tree species diversity in Abu-Gadaf natural forest reserve.

Abu-Gadaf Natural Forest Reserve (ANFR) is a state natural forest present in the Blue Nile Region offering various ecological, economic, and social functions to local communities in Abu Gadaf, Amri, and Mukla villages as specific, and the Blue Nile and Sudan as general. The rural community around the reserve keeps domestic animals such as goats, sheep, cows, and camels, as well as, practice farming, charcoal production, edible forest fruits gathering, and honeybee collection (Hassan et al. 2022; Mohammed, Hassan, et al. 2021). Moreover, the current documented biotic and abiotic disturbances in ANFR can change the forest structure and influence its diversity and carbon sinks. Therefore, this study could potentially contribute to the conservation and sustainable management of ANFR resources and its vulnerable species.

The sustainable management of forest reserves and similar conserved sites requires detailed information about the reserves' species diversity, stand characteristics, dendrometric properties, site index, biotic and abiotic disturbances, healthy status, and site dynamics, achievable through forest inventory (Heym et al. 2021; Mohammed et al. 2022). While dendrometric parameters like diameter at breast height and total tree height can easily be assessed using ground measurement, tree volume and biomass can precisely computed and predicted using linear and non-linear models (Dimobe et al. 2019; Ibrahim et al. 2015; Zhou and Hemstrom 2009). Moreover, allometric models can accurately be initiated to assess the aboveground biomass for mixed tree species or specific ones (Dimobe et al. 2019; Tetemke et al. 2019). Therefore, for the computation of biomass above ground, this study used a model recommended for tropical forest trees (Dimobe et al. 2019).

The study suggests that areas with adult and codominant trees store more carbon than juvenile ones. Additionally, sites frequently distressed with unpermitted utilization (harvesting, grazing, browsing, and ground fire) have less species diversity, stocking density, and juveniles. Accordingly, the outcomes of this study will form a solid ground for the integrative management of ANFR and other similar ecosystems.

2. MATERIALS AND METHODS

2.1. Study area

The study took place in ANFR, which is found in Blue Nile Region at 11º 25′ 00″ N, 11º 31′ 00″ N, 34º 50′ 00″ E, and 34º 55′ 00″ E (Figure 1) (Mohammed, Hassan, et al. 2021). The reserve is characterized by a mean monthly minimum and maximum temperature and rainfall of 22 ºC, 43 ºC, 20 mm, and 300 mm, respectively (Mohammed, Hassan, et al. 2021). Though the forest topographically has flat and rocky sites, the well-established tree species are *Acacia seyal*, *Boswellia papyrifera*, *Combretum hartmannianum*, and *Ziziphus spina-christi* (Hassan et al. 2022). Moreover, non-timber forest product trade and fuelwood business are among the common income producing practices in the area Hassan et al. 2022). In addition to that, as ANFR is closer to the Dinder Biosphere Reserve, various wild animals can frequently observed in the forest during the rainy season, particularly Warthog, waterbuck deer, *Acacia seyal* monkey, and migratory birds (Mohammed, Hassan et al. 2021).

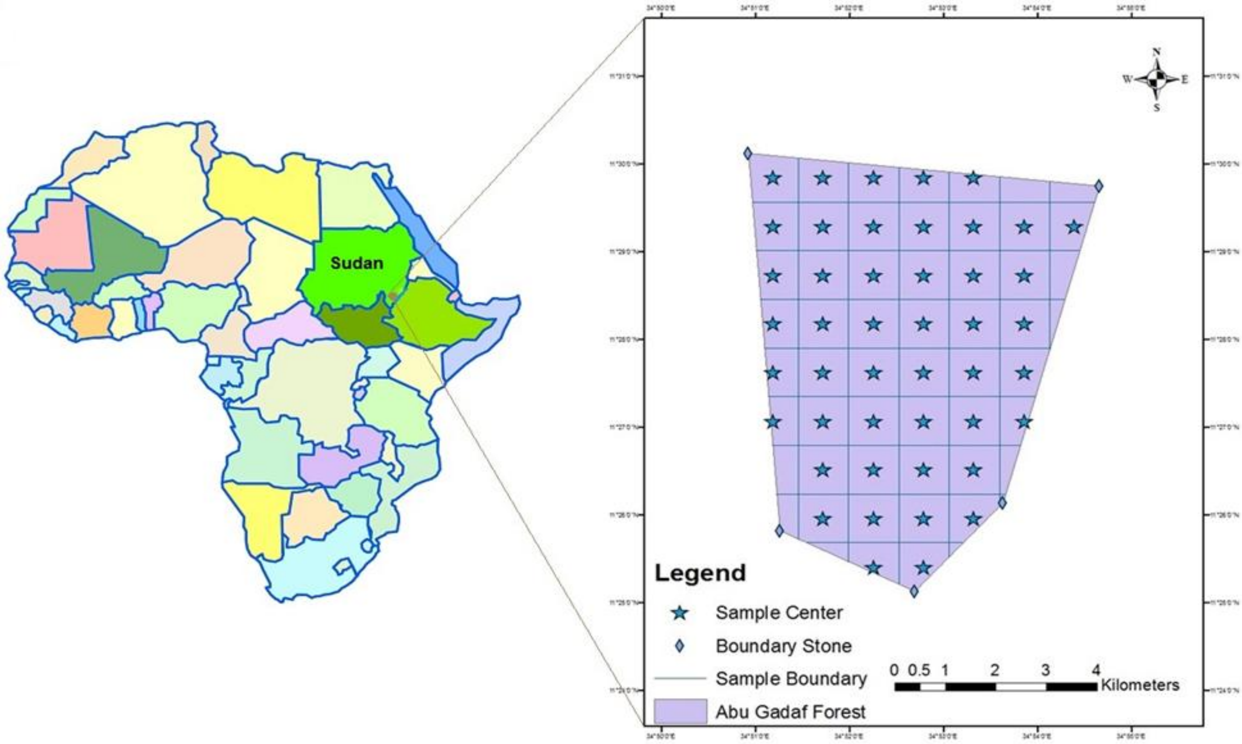

Figure 1. The map displaying the study area and the inventoried sample plots.

2.2. Data collection

The study used the stratified sampling design with a systematic layout of sample plots within the stratum. Data collection occurred from December 2021 to May 2022 in 46 sample plots of 1000 m^2. The dendrometric features like diameter at breast height (DBH), total tree height (H), and crown properties were measured for all inventoried trees with DBH ≥ 5 cm (Mohammed et al. 2022). While biomass stock was computed using equation 1, the amount of carbon was assessed by multiplying the value of aboveground biomass by 0.47 (a default C fraction as documented by the Intergovernmental Panel on Climate Change) as recommended by (Dimobe et al. 2019; Gebeyehu et al. 2019; He et al. 2022). Moreover, the Shannon and richness indices were calculated as a proportion of a specific species to overall ones and the total number of species, respectively (Dimobe et al. 2019; Mohammed, Hassan, et al. 2021). Additionally, evenness was computed as a division of the Shannon diversity index to the species richness index (Dimobe et al. 2019).

Aboveground biomass (AGB) = $0.0673 * (\rho * DBH^2 * H)^{0.976}$ ……………………………… (1)

Where ρ is the mean wood density as computed from the international database records (Dimobe et al. 2019), and H is the overall tree height.

2.3. Data analyses

The allometric linear models in R software were performed for dendrometric parameters-carbon stocks and diversity indices-carbon stocks relationships (Dimobe et al. 2019). Trees were classified into five classes based on DBH for further comparison and correlations. Moreover, analysis of variance and Tukey test were run within the stratum and between strata comparisons for detailed comparison purposes and determination of the statistically significant differences, respectively (Hassan et al. 2022; Mohammed et al. 2022). Besides that, tree density and relative abundance were assessed as the total number of stems per hectare and the abundance of a specific tree species to the overall ones of all species multiplied by 100, respectively (Mohammed, Hassan, et al. 2021). The excellent, good, fair, poor, and none regeneration trends were classified based on references (Idrissa et al. 2018; Mohammed, Hassan, et al. 2021) as reported in Table 1.

Table 1: The criterions for regeneration trends classification

No	Trend	Criteria
1	Excellent	Seedlings are twice saplings and saplings are greater than adults
2	Good	Seedlings are greater than saplings and saplings are greater than adults
3	Fair	Seedlings equal saplings and saplings are greater than adults
4	Poor	No seedlings, only saplings and adults
5	None	No seedlings and saplings, only adult trees

3. RESULT AND DISCUSSION

3.1. Tree species diversity and composition

The lowland areas display less tree species diversity in comparison to highland ones for Shannon diversity index, species evenness index, and species richness index, with significant differences between sites (Figure 2). While diameter at breast height and total tree height in the highland area were greater than that of lowlands by > 60%, the tree density of adult tree species in the lowlands was half that of highlands, with significant differences within and across the sites (Figure 2). Moreover, *Acacia seyal, Anogeissus leiocarpus, Balanites aegyptiaca, Boswellia papyrifera, Combretum hartmannianum, Lannea fruticosa, and Ziziphus spina-christi* dominate both high and land areas with clear representation of Fabaceae family members (Table 2). The forest accommodates 45 and 30 tree species in its high and lowland areas, respectively (Table 2).

These significant differences between the low and highlands of Abu-Gadaf natural forest reserve in terms of species diversity show how lowland areas were severely affected by human practices in forms of unpermitted harvesting, mechanized farming, overgrazing by livestock, and forest fire due to honeybee collection. These findings are in line with (Dunne et al. 2011; Ibrahim and Hassan, 2015; Kikoti et al. 2015; Suleiman et al. 2017; Yeneayehu et al. 2019), who illustrated that human activities influenced the species diversity in the natural forests and game reserves of Kenya, Sudan, Tanzania, Nigeria, and Ethiopia, respectively. Moreover, the high appearance of Fabaceae family members can be associated with the wide ecological range of their species as well as their high adaptability. However, the small diameter at breast height and low total tree heights in the lowland areas alert for further conservation and protection measures, particularly for vulnerable species and those with a limited relative abundance and importance value index.

3.2. Biomass, carbon stocks, and dendrometric relationships

While medium and large-sized trees showed significant differences between sites for both aboveground biomass and carbon stock, small-sized trees exhibited no variation between low and highlands for the two parameters (Figure 3). The biomass of adult and mature trees (large-sized trees) in highlands was double that of lowlands and significantly differed (Figure 3). The carbon stock-diameter at breast height relationship illustrated a strong polynomial correlation with R^2 value of 0.93 (Figure 4). However, the total tree height-carbon stock relationship displayed a weak correlation with 0.32 as R^2 (Figure 4).

Table 2: The present/absent, importance value index, and regeneration trends of tree species assessed in the high and lowlands of Abu-Gadaf natural forest reserve

Species	Present (+) and Absent (-) of		Importance Value Index		Regeneration Trends	
	Highland	Lowland	Highland	Lowland	Highland	Lowland
Acacia polyacantha Willd.	+	+	3.412	3.439	I	I
Acacia senegal (L.) Willd.	+	+	10.961	19.22	II	III
Acacia seyal Del.	+	+	18.22	25.68	III	IV
Adansonia digitata L.	+	+	9.179	10.02	I	I
Anogeissus leiocarpus (DC.) Guill.	+	+	20.51	16.88	IV	III
Balanites aegyptiaca (L.) Del.	+	+	18.10	15.29	IV	III
Boscia senegalensis (Pers.) Lam.	+	-	3.575	-	I	0
Boswellia papyrifera (Del.)	+	+	15.83	16.02	III	III
Combretum aculeatum Vent.	+	+	2.566	6.376	I	I
Combretum ghasalense Engl. &	+	-	6.560	-	I	0
Combretum glutinosum Perr. ex	+	+	9.095	11.18	III	III
Combretum hartmannianum	+	+	26.70	23.95	IV	III
Combretum micranthum G. DON	+	-	4.188	-	I	0
Combretum molle R. Br ex G.	+	-	2.068	-	0	0
Commiphora africana (A. Rich.)	+	+	3.093	3.810	I	I
Dalbergia melanoxylon Guill. et	+	+	5.054	6.261	II	II
Dichrostachys cinerea (L.) Wight	+	+	2.657	7.069	I	0
Diospyros mespiliformis Hochst.	+	+	4.417	5.435	I	0
Entada africana Guill. et Perr.	+	+	2.175	6.351	I	0
Ficus sycomorus	+	+	1.049	4.568	0	0
Gardenia lutea Fresen.	+	+	3.843	4.789	I	I
Grewia bicolor Juss.	+	-	1.520	-	0	0
Grewia flavescens Juss.	+	-	1.844	-	0	0
Grewia mollis Juss.	+	-	2.134	-	0	0
Hyphaena thebiaca (L.) Mart.	+	+	6.139	7.518	II	II
Lannea fruticosa (Hochst. ex. A.	+	+	16.88	25.12	III	IV
Lannea kerstignii Engl. & K.	+	+	1.499	1.835	0	0
Lannea nigritana (Scott Elliot)	+	+	8.951	7.921	II	II
Lannea schimperi (Hochst. ex. A.	+	-	4.212	-	0	0
Maerua angolensis DC.	+	-	2.690	-	0	0
Piliostigma reticulatum (DC.)	+	-	2.136	-	0	0
Pseudocedreca kotschyi	+	-	7.035	-	0	0
Pterocarpus lucens Lepr. ex Guill.	+	-	5.846	-	0	0
Sclerocarya birrea (A. Rich)	+	+	5.660	12.07	II	II
Sterculia africana (Lour.) Fiori.	+	+	6.132	7.474	I	I
Sterculia setigera Del.	+	+	13.66	8.786	II	II
Stereospermum kunthianum	+	-	2.138	-	0	I
Strychos innocua Del.	+	+	2.959	6.302	I	I
Syzygium guineense (Willd.) DC.	+	-	4.492	-	I	0
Tamarindus indica L.	+	+	2.130	6.810	I	I
Terminalia brownii Fresen.	+	+	1.549	3.937	0	0
Terminalia laxiflora Engl.	+	+	5.949	7.286	I	I
Terminalia macroptera Guill. &	+	+	6.196	7.568	I	0
Ziziphus abyssinica Hochst. ex. A.	+	-	1.228	-	0	0
Ziziphus spina-christi (L.) Desf.	+	+	12.77	11.07	III	III

Symbols 0, I, II, III, and IV are referred to none, poor, fair, good, and excellent regeneration trends.

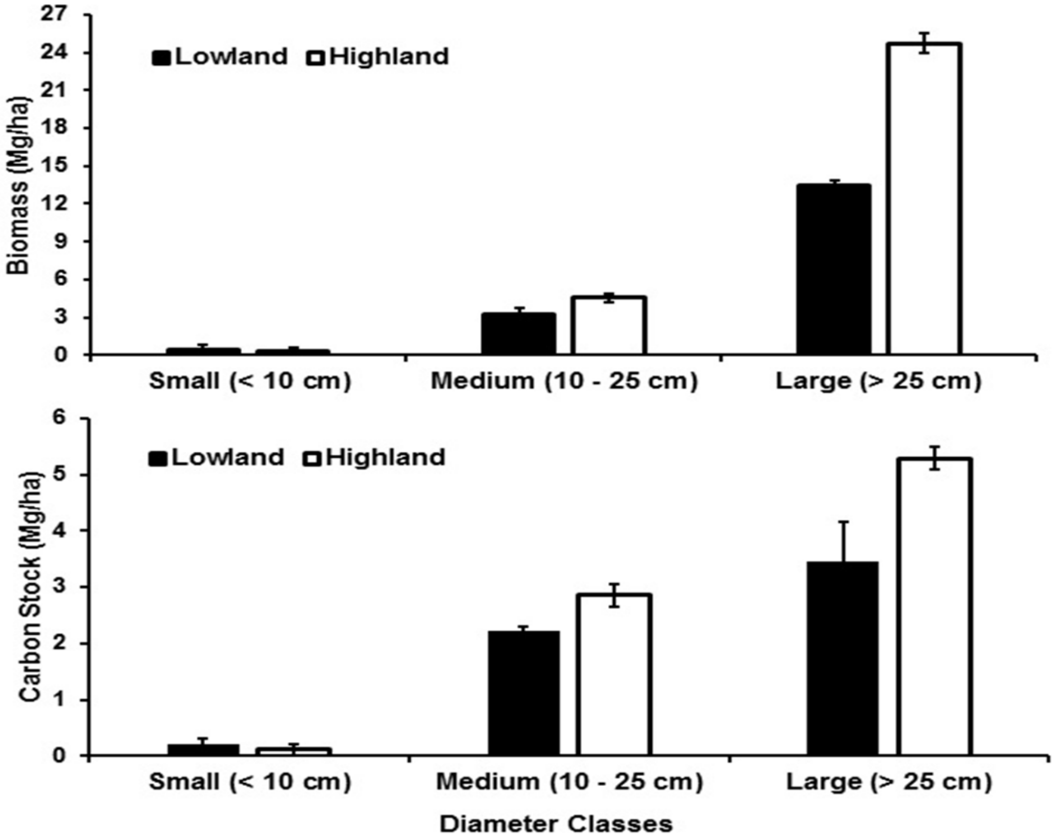

Figure 2: Tree diversity, dendrometric parameters, and density for the cruised tree species in the low and high lands of Abu-Gadaf natural forest reserve (α = 0.05).

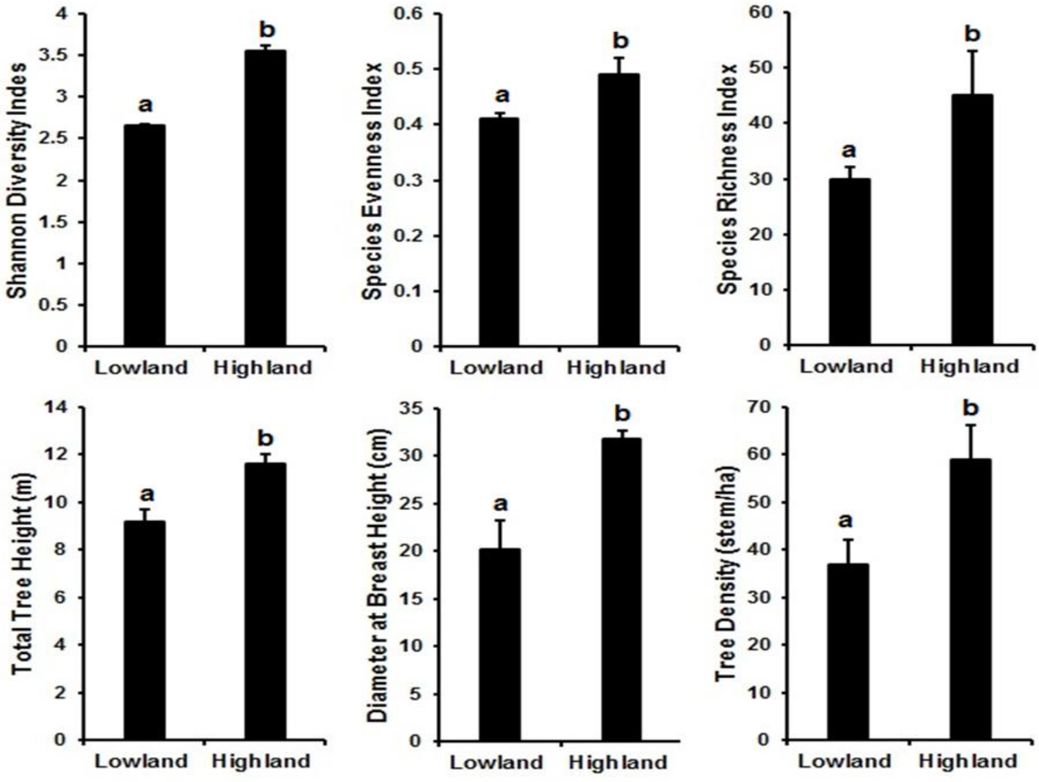

Figure 3: Aboveground biomass and carbon stock for different diameter classes of the identified tree species in the low and highland sites of Abu-Gadaf natural forest reserve (α = 0.05).

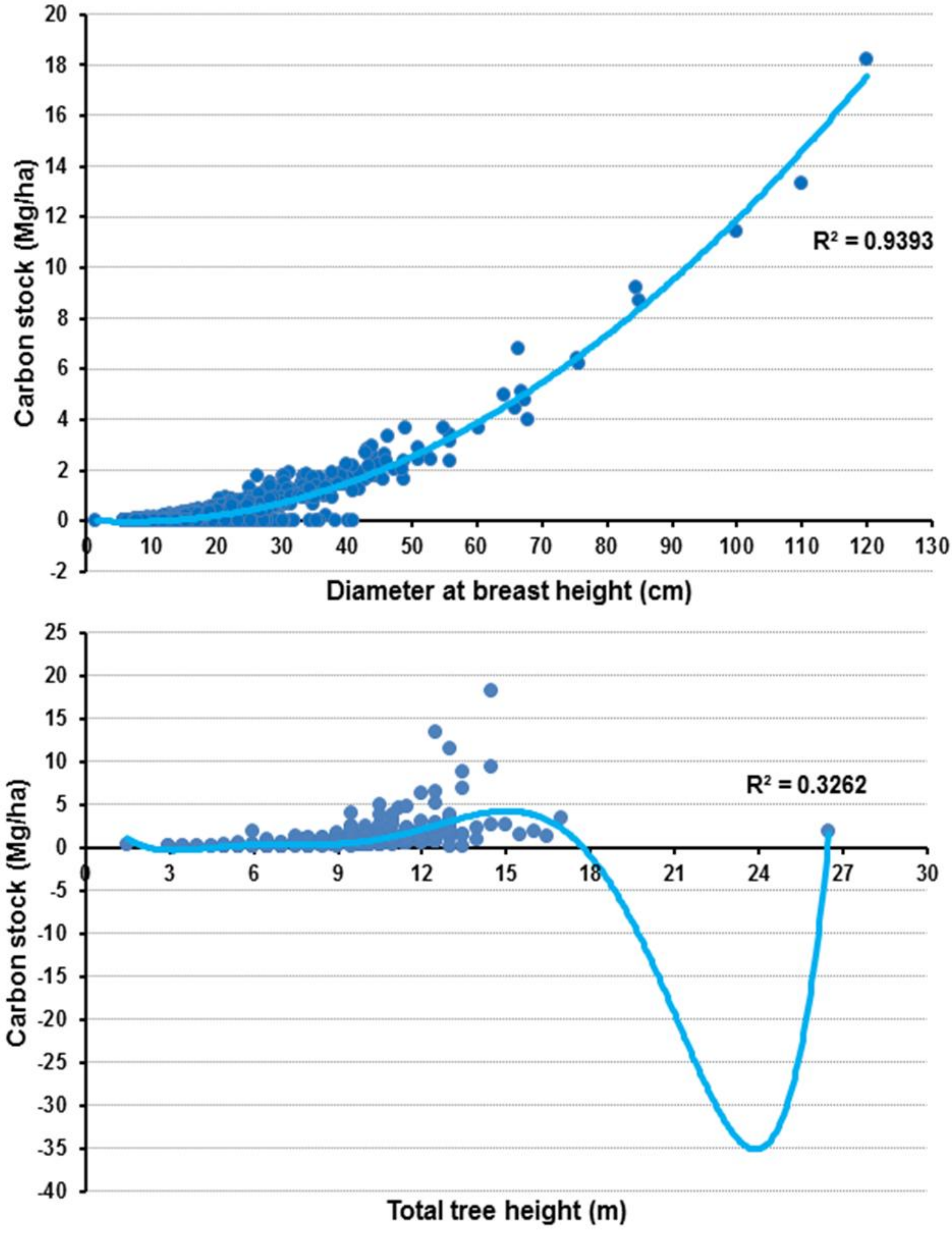

Figure 4: Polynomial relationships between the average tree diameter at breast height, total tree height, and the carbon stock for the identified tree species in Abu-Gadaf natural forest reserve

The high values of aboveground biomass and carbon stock for the medium and large-sized trees highlight the importance of dominant and codominant trees in sequestrating and storing CO_2 through their vigorous rates of photosynthesis and metabolism. Though young plants (seedlings and saplings) have a rapid growth rate at favorable conditions, still have fewer cells and cell divisions compared to adult and mature trees. However, the tree crown and diameter properties vary according to the tree species (broadleaved or narrowleaved), biotic disturbances (grazing, browsing, harvesting, invasive species, and diseases), abiotic disturbances (lighting, flooding, earthquakes, extreme weather, and pollution), and site conditions (soil health, competition, immigration, and migration), and therefore, the biomass content and carbon stock. These findings are consistent with (Amahowe et al. 2018; Dimobe et al. 2019; Ouédraogo et al. 2019; Zhu et al. 2021).

Furthermore, the observed variation between high and lowland sites of the Abu-Gadaf natural forest reserve in terms of biomass and carbon stock is directly associated with intensive pollarding activities as well as livestock browsing. The researchers (Carozzi et al. 2022; Chen and Tang, 2016; Osem et al. 2017) concluded similar results. Moreover, the strong relationship between tree diameter and carbon stock illustrates the potential of tree diameter to predict the tree carbon stock if properly modeled. Therefore, as forest inventory consumes time and human resources, modeling approaches can overcome these constraints and pave the road for growing stock assessment in both accessible and inaccessible forest sites.

4. CONCLUSION

The study findings illustrated that highland areas have high species richness, evenness, and Shannon index value with 45 tree species and excellent regeneration for dominant tree species. However, the lowlands accommodate 30 tree species with low tree density and aboveground biomass. Moreover, the carbon stock-tree diameter relationship exhibited a strong polynomial correlation with R2 value of 0.93 in comparison to carbon stock-height ones. While the reserve hosts a considerable number of tree species, particularly in the highland areas, several none regenerated species in the lowland sites need a quick intervention for further conservation. Accordingly, the participatory approach of community forestry can successfully guide the restoration plan of the influenced areas across the reserve. Species like Acacia senegal, Balanites aegyptiaca, Boswellia papyrifera, and Ziziphus spina-christi can potentially use for afforestation of the degraded sites due to their economic values and high resiliency.

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