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Estimating Ecological Characteristics and Carbon Stock in Uneven-Aged Plantations of *Acacia senegal* L. in the Savannah Woodlands of Sudan

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Abstract

The aim of this study was to assess *Acacia senegal* trees' characteristics as well as evaluate the carbon stock under a variety of ages in the El Demokeya forest in Sudan, where the Gum Arabic belt is located. 12 sample plots, in 2021 were randomly distributed to represent the entire area of the forest prior to the required measurements. The sample was designed as squire plots with one hectare. In each sample plot, all trees were counted, their height (m), and Diameters Breast Height (DBH in cm), respectively. The results showed the highest number of trees per ha at age 20 years old and the lowest number at age 47 years, while the highest values of DBH and volume were found at age 47 years old. As a result, the maximum and minimum values of the aboveground biomass were found in the age 47 years old and 16 years, accounting for 19.87 tons and 1.9 tons respectively. Thus, the amount of carbon stock was 11.92 tons/ha in the 35-years-old and 1.19 tons/ha in the 21-year stands. Furthermore, the average carbon stock in all plots was estimated as 18.70 tons/ha and hence the total carbon stock in the El Demokeya forest is equal to 620.11 tons. Conclusively, the characteristics of trees, amount of aboveground biomass and carbon stock in the El Demokeya forest varied among the uneven-aged plantation groups. The study recommends and encourages the protection of *A. senegal* in order to increase the carbon sink as well as protect the environment in the era of climatic changes.

Keywords

Aboveground Biomass, Soil Organic Carbon, Dry Lands Forest, Climate Change Mitigation, Carbon

1. Introduction

Dry lands, are known as lands where the ratio of annual precipitation and mean annual potential evapotranspiration (aridity index) is between 0.05 - 0.65 [1] [2]. It covers approximately 41% of the total landed area of the Earth planet [3]. In Africa, dry land forests are used as a resource for livelihoods and economic development [4], and environmentally they contain 16% - 25% of the global Soil Organic Carbon (SOC) stock [5]. Keeping in view, the amount of annual rainfall in these lands is one of the important factors that control the limited production of biomass [3] [6]. Particularly, the vegetation cover loss in the dry lands of the Sub-Saharan region is caused by land degradation, which decreases biological productivity, which consequently lessens and affects the SOC consents and their natural potentials [6] [7] [8] [9]. The degradation of dry lands has been considered as a global environmental problem associated with desertification, biodiversity loss and climate change [7]. Biological productivity and SOC would not only affect the local and regional environment, but also would contribute to global climate change mitigation by decreasing CO_2 in the atmosphere [3].

Sudan is one of the Sub-Saharan African countries that occupy 1.88 million ha, where 92% of its total area is classified as dry lands [3] [8]. Forest resources are considered among the most important natural features where they form with the other varying entities of plants that cover the base for the terrestrial ecosystem of the country [9]. Fortunately, the dry lands of Sudan are endowed with good forest resources and vegetation cover, which play an important environmental role against desert creeping southward. This hinders soil erosion and land degradation [10]. For instance, the Gum Arabic gardens (mainly planted by *Acacia senegal*) represent 48.44% of the total area of forest plantations in the dry lands of Sudan [8] [11].

Acacia senegal is an important indigenous multipurpose tree, it is known for the provision of non-wood forest products and many other ecosystem services [12]. Particularly, Gum Arabic has economic benefits in commercial industrial applications and local uses [13] [14] [15]. Accordingly, these are known to play a great role in carbon sequestration, and therefore in climate change mitigation, if they are left intact [16]. In addition to its advantage in enhancing soil production, restoration of soil fertility and reclamation of the negative impact of climate variability and irrational land use [17]. However, *A. senegal* is under severe pressure associated with population growth and their interventions for different purposes such as: cutting trees for farming, firewood, and building, which subsequently has substantially reduced the area it covers and carbon pools over time [16]. However, few studies in western Africa have been carried out on the relationships between SOC contents and tree characteristics in dry land [18] [19] [20], while few studies in Sudan have been focused on types and characteristics of vegetation cover and SOC [21] [22]. Therefore, important to assess the contribution of *Acacia senegal* plantations and the impact of their degradation on the global carbon cycle and the amount of soil organic matter necessary to obtain data as sources of carbon.

This study aims to appraise SOC, trees carbon stocks under the *A. senegal* plantations and their biophysical characteristic in the El Demokeya Forest in Northern Kordofan State of Sudan, also specifically compare tree volume, and AGB under plantations. The study has hypothesized that SOC stocks would be greater where tree density is high, also SOC will be correlated with the stand's age class.

2. Materials and Methods

The study area is located in El Demokeya forest reserve in Sudan. More specifically, the investigated area was established in 1959/60 to rehabilitation of gum Arabic belt about 3150 ha. It is the biggest reserved forest of pure *A. senegal* "Hashab" stands in the Sudan [23], located about 30 km East of Elobeid town in North Kordofan State, in the dry region of central Sudan. North Kordofan State is located in the Sudan's dry lands, which refers to an ecological zone that is bordered by the desert region in the north and the sub-tropical dry forest in the south (**Figure 1**). This State extends roughly between the latitudes of 9˚30'N and 16˚24'N and longitudes of 27˚E to 32˚E, where the gum Arabic belt is located [16] [24]. The distribution of its communities consists of 50% rural, 34% urban, and 16% pastoralist, where their main economic and livelihood activities are rain-fed agriculture and livestock rearing [25]. The study area is dominated by Hashab (*Acacia senegal*), Merikh (*Leptadenia pyrotechnica*), Tomam grass (*Panicum turgidum*), Kitir (*Acacia millifera*), Seyal *(Acacia tortilis* var. spirocarpa), and Higlig (*Balanites aegyptica*) [25] [26] [27]. Sandy soils and sand dunes or Al Quoz mainly characterize soil, while Gardud soils are not subject to cracking in the south [27] [28]. The climate of the study area is semi-arid where the rainy season expands from June to October, and the peak of precipitation occurs in August with an average of 250 - 400 mm [29]. Moreover, the summer season usually starts in February, it ends in June, with high temperatures ranging from 28˚C - 30˚C, and it reaches the highest level in April with an average temperature of 33˚C [30].

2.1. Data Collection

2.1.1. Sample Plots Design, Field Measurements and Sampling

During July 2021, twelve square plots (100 m × 100 m; **Figure 2**) were randomly identified and distributed to represent the entire area of the forest prior to the

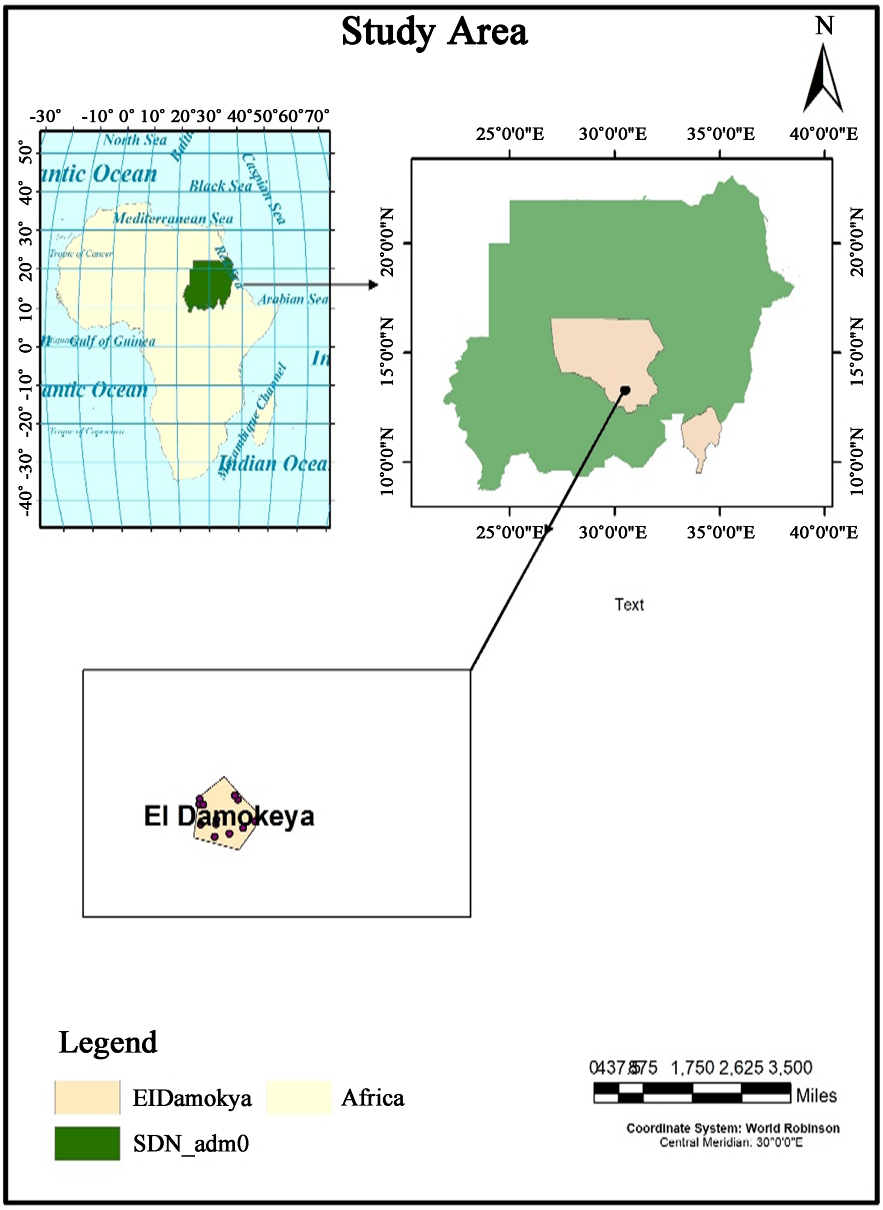

Figure 1. Map showing the location of study area and in Africa (upper left corner), Sudan (upper left corner), and North Kordofan (bottom).

required measurements. El Demokeya forest comprises from four aging classes, therefore three plots were identified for each category. In each plot all trees were counted, their height (m) and Diameters at Breast Height (DBH in cm) were measured using the Hager and Caliper, respectively.

Soil samples were collected simultaneously with trees measurements from the 12 plots under plantation of *A. senegal*. In each plot, five soil samples were collected (*i.e.* from the four corners and the plot's center; **Figure 2**). These five locations were sampled within an area of 15 cm × 15 cm under the tree's canopy at distance of 0.5 m from the main stem following methodology as described in Abaker *et al.* [29]. Soil samples were collected at three different depths (*i.e.* 0 - 15 cm,

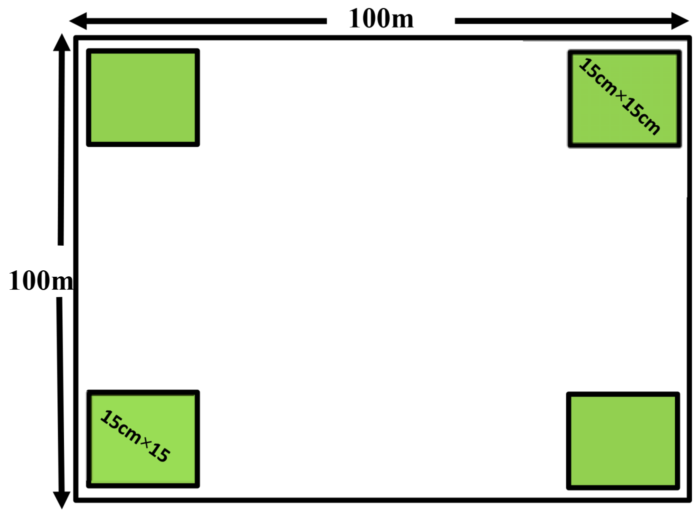

Figure 2. Schematic presentation of one plot at the studied sites as well as the location of the five different sampling points (15 × 15 cm square).

15 - 30 cm and 30 - 45 cm), and later they mixed to form a composite sample, then taken in labeled plastic bags to laboratory to determine SOC concentration. Soil bulk density of the collected sampling locations was also determined. The collected soil samples were firstly air-dried for 48 hrs, cleaned from leaves, roots and litters, crashed and passed through 2 mm sieve and then particles that less than 2 mm have taken for chemical and physical analysis. For physical analysis, bulk density determination method was used the core method of Blake and Hartge [31], which is recommended because of the difficulty in taking intact volumetric samples from loose sandy soils with no structure as in study sites.

2.1.2. Data Analysis

The parameters measured are trees' diameter DBH (cm), tree height (m) and the number of individual trees in each plot with an area one ha (*i.e.* density/ha). DBH was measured using a perimeter ruler with a starting diameter of 5 cm, tree height was measured accordingly [32], methodology, then tree basal area, volume and biomass were determined using the following equations:

$$\text{Basal Area}(\text{M2}) = \frac{\pi * (\text{DBH})^2}{4 * 100} \tag{1}$$

$$\text{Tree Volume}(\text{M3}) = \text{BA} * \text{H} * \text{FF} \tag{2}$$

where:

DBH: diameters at breast height;

FF: Form Factor of *Acacia senegal* tree = 0.45;

BA: Basal Area of each tree;

H: Height of tree (m).

Furthermore, trees diameters frequencies were calculated using eight classes with 3 cm intervals (*i.e.* <3 cm, 3.1 - 6 cm, 6.1 - 9 cm, 9.1 - 12, …, 21.1 - 24) cm, which signposted the dominant diameter classes among El Demokeya trees. In addition, density of *Acacia senegal* trees per ha was assessed using the number of trees found in each plot using the equation recommended by [13] [15].

$$\text{Trees density/h} = \sum_{i=n}^{n} d/n \tag{3}$$

where:

d = the stem number/plot and n is the number of plots.

For biomass calculations [33], Equation (6) was applied. This equation logically suits *Acacia senegal* biomass calculation according to the values of measurements obtained in the inventory. It thought that the climatic conditions such as rainfall is ranging from dry to less than 1500 mm and the diameter that up to 25 cm are suiting the requirement of applying this equation where it relay on one independent variable (DBH) [34].

Keeping in view, tree biomass is often calculated separately (*i.e.* Above Ground Biomass (AGB), Below Ground Biomass (BGB)). The below ground biomass was estimated by taking 0.2 of the above ground biomass [35]. Consequently, the stock carbon is estimated as 50% of the total biomass [36] [37].

$$\text{Y} = 0.139 * \text{DBH}^{2.32} \tag{4}$$

$$\text{X} = \text{Y} * 0.2 \tag{5}$$

$$\text{TB} = \text{Y} + \text{X} \tag{6}$$

where:

DBH: Diameters at Breast Height; Y = Above Ground Biomass (t/ha); X = Below Ground Biomass (t/ha), and TB: Total Biomass (t/ha).

2.1.3. Quantifying Soil Carbon

Soil Organic Matter (OM) estimate was realized using the Walkley and Black [38] protocol, where the collected soil samples (fraction less than 2 mm) from three depths were treated with 20 ml H_2SO_4 (*i.e.* 98% concentration) and 10 ml $K_2Cr_2O_7$ to consume and oxidize the organic carbon through a titration with Ammonium Ferrous Sulfate (0.1 N) as shown in Equation (8).

$$\text{O.M\%} = \frac{(\text{VB} - \text{VS}) * \text{N} * \text{EW} * 1.33}{\text{g} * 1000} * 100 \tag{7}$$

$$\text{SOC}(\text{ton/ha}) = \frac{\text{BD} * \text{OM\%} * 0.58 * \text{H}}{100} \tag{8}$$

whereas:

O.M = Organic Matter; VB = Volume Ammonium Ferrous Sulfate consumed by Blank; VS = Volume Ammonium Ferrous Sulfate consumed by Sample; N = Normality of Ammonium Ferrous Sulfate; EW = Equivalent Weight for Carbon; G = Soil Weight in grams; SOC = Soil Organic Carbon; BD = Bulk Density; H = Sample Depth.

2.1.4. Statistical Analysis

The analysis were done for plantation age of characteristics tree and AGB (t/ha), BGB, SOC (%) we used the descriptive analysis in Excel software. We used one-way Analysis of Variance (ANOVA) to tested the effect of plantation age and plantations characteristics on plot mean of total biomass and Carbon Stock (t/ha) under plantations followed test by LSD test, were preform statistical Analysis of Variance (ANOVA), we used the SPSS software (IBM SPSS Statistics for window, Version 26).

3. Results

Trees measurements have revealed to different biophysical characteristics of *A. senegal* species in El Demokeya forest, where the different range of tree DBH and height, tree basal area, average number of trees per ha were identified. The average DBH, height, basal area, volume and trees' number per ha for *A. senegal* is 5.9 cm, 3.39 m, 94.54 m^2, 201.11 m^3 and 228 Tree/ha respectively (**Table 1**). Although, the average of tree characteristics could depict the real status of each plot, their DBH frequencies were quite varied among the fourth age classes. Thus, deducing from **Figure 3**, the highest frequency in the DBH was found in class 0 - 3 and the lowest frequency in class 21 - 24.

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3.1. Abundance, Frequency and Biodiversity

Sixteen tree species belonging to the eleven families were recorded in Adomoki-ya reserved forest (**Table 2**). *Acacia senegal* from the family of Fabaceae was the most dominant with a frequency of 88.05%, the remind species have circa frequency in the site with 1.7.3%, 1.55%, and 1.24% for *Boscia seneglaensis*, *Acacia melefera*, and *Calotropis procera* respectively (**Table 2**)

3.2. Quantity of Biomass, Biomass, Soil Organic Carbon, Total Carbon Stock per Hectare

General statistical results of soil Organic carbon and quantity of biomass from sites including mean, minimum, maximum, and SD are shown in **Table 3**, as well as the averages of trees biomass (*i.e.* Above Ground Biomass (AGB) and Below Ground Biomass (BGB) and Soil Organic Carbon (SOC). The Maximum and

Table 1. Average tree characteristics.

Age Categories	Tree Characteristics				
	D (t/ha)	DBH (cm)	H (m)	BA (m^2)	V (m^3)
16	84	3.13 ± 2.6	2.6 ± 0.65	31.02	44.61
21	122	3.57 ± 2.6	2.99 ± 0.65	42.17	70.63
35	347	7.63 ± 2.6	3.65 ± 0.65	78.94	154.3
47	415	9.13 ± 2.6	4.31 ± 0.65	226.04	534.89
Mean	242	5.9	3.39	94.54	201.11

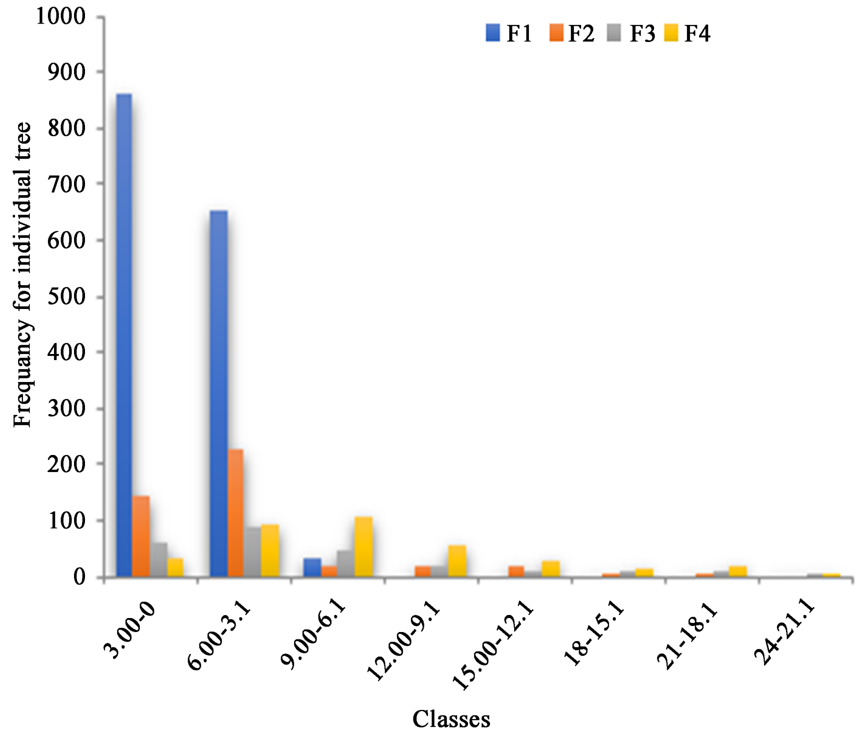

Figure 3. Class of tree DBH and their frequencies in the fourth age categories (*i.e.* F1 = 16, F2 = 321, F3 = 35, F4 = 47).

Table 2. List of the tree species identified in the El Demokeya forest, their abundance and frequency status.

Scientific Names	Family	Abundance	Frequency (%)
Acacia senegal	Fabaceae	2902	88.05
Acacia seyal	Fabaceae	18	0.55
Acacia albida	Fabaceae	6	0.18
Cadaba ablongifolia (*Cadaba rotundifolia*)	Capparaceae (Capparidaceae)	59	1.79
Salvadora persica	Salvadoraceae	67	2.03
Leptadenia pyrotechnica	Apocynaceae	16	0.49
Acacia mellifera	Fabaceae	51	1.55
Adansonia	Malvaceae	3	0.09
Sterculia africana	Sterculiaceae	25	0.76
Boscia senegalensis	Capparaceae (Capparidaceae)	57	1.73
Calotropis procera	Pocynaceae	41	1.24
Balanites egyptica	Balanitaceae	13	0.39
Tamarindus indica	Fabaceae	9	0.27
Ziziphus spina-christi	Rhamnaceae	23	0.70

minimum AGB values were found in age 47 yrs and 35 yrs which account for 3.6494 and 1.1586 ton/ha, respectively. Accordingly, the amount of Soil Organic Carbon was Maximum (1.3 ton/ha) in age 21 yrs and minimum in age 16 yrs as (0.2 ton/ha). The results show SOC under the *A. senegal* plantation in all ages was calculated as approximately in range 0.1 - 0.8 t/h with mean 0.55 t/h (Table 3).

Despite of the ANOVA analysis, in general ANOVA showed that total biomass were ($p < 0.05$) highly significant difference in the mean total biomass between these four age classes. On other hand, the carbon stock per ha also, showed highly significant difference between all ages with ($p < 0.05$).

In general, T.C (t/ha) ecosystem were higher with plantations age, especially with oldest age which is showed in Figure 4. The total carbon stock of the oldest plantation (47-year-sold) was 12.03% greater than other plantations age, we justify that difference for Carbon Stock to increase the density of trees. On the other hand, also Figure 4 showed Total Biomass increased with the plantation age, the greater value in 47 year-old while the lower value in 16-years-old.

Moreover, the estimated carbon stock as 1.29745 tons/ha. The estimation of the total carbon stock provided rather good results for SOC in all locations,

Table 3. Average of aboveground biomass, belowground biomass, soil organic carbon.

Age Categories	Tree Biomass and Carbon		Soil Carbon Stock
	AGB (t/ha)	BGB (t/ha)	SOC (t/ha)
16	1.9 ± 7.19	0.4 ± 1.44	0.8 ± 0.26
21	2.9 ± 7.19	0.6 ± 1.44	0.6 ± 0.26
35	5.9 ± 7.19	1.2 ± 1.44	0.7 ± 0.26
47	19.87 ± 7.19	3.9 ± 1.44	0.10 ± 0.26
Mean	7.66	1.54	0.55
Min	1.1586	0.2371	0.02
Max	3.6494	0.7299	0.13

AGB = Above Ground Biomass, BGB = Below Ground Biomass.

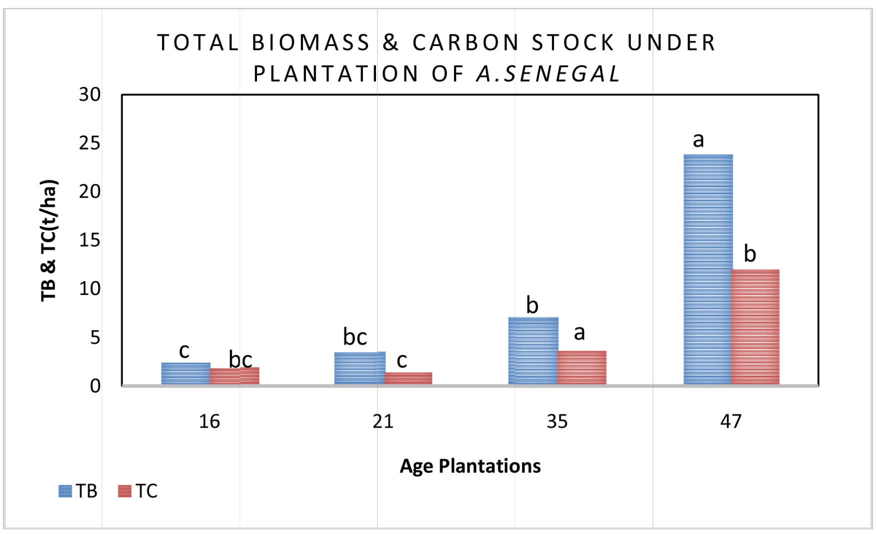

Figure 4. Mean total biomass and total carbon stock for *A. senegal* plantation of different ages at El Demokeya forest.

which was resulted with 43.028 ton.

4. Discussion

The four ages in this study were selected to assess contribution of *Acacia Senegal* trees' characteristics as well as evaluating the carbon stock under four ages at 12 plots. Given the difference in site conditions, we wanted to check for variation in tree characteristic between ages.

4.1. Distribution of Tree Volumes in the Four Age Classes

El Demokeya forest is often known to be dominated by *A. senegal* tree species, which is one of the most important and premium species that produce Gum Arabic in the savannah woodlands. Through this study, we found that the value of trees DBH affects the volume of trees and it is directly proportional to their volume by retrieving from the results showed the highest value of tree volume was found in the plot that planted in 1987. Although, the number of trees in this plot was not high, the high DBH values have played a main role in tree volume this result similar to [39] as they found there is a relationship between DBH and volume of trees. Moreover, the lowest value of the tree volume was found at age 21 yrs due to small value of their DBH. This may have been affected by the low value of DBH as the trees were at small age. This is in line with [40] [41] [42] which concluded that the volume of tree is not only depending on the number of trees, but rather, on their DBH values.

4.2. Above Ground Biomass in Relation to the Number of Trees and DBH

In this study, conducted biomass values it returned to the DBH values, there is strong relationship between them, the higher value of AGB is depending to DBH values this matches with study of [43]. However, the biomass values showed positive result where the lowest biomass value has occurred. Thus, it could be said that the number of trees would not upturn the biomass value. This is coherent with Forrester findings where his concord the increment of an area's biomass is totally depending on the high-values of trees' DBH rather than their number in that area, which is in agreement the work done [44].

4.3. Carbon Stock in El Demokeya Forest

Many studies agreed that the ligneous tree species have important role in carbon stock sequestration in arid land [16]. In this study, we obtained the carbon stock (1.276 ton C/h) that is due to hard condition in this region, this value lower than study of Temgoua *et al.* [45] who concluded the carbon stock in Aciaca Senegal plantation cric (9.6 T/h) in far North Cameroon [45]. That similarly with Daakreo he found the Carbon stock for Acaica Senegal 8.4 ton c/h in Chad [46], that difference between values are explained the fact of that our study took place in the degraded stands with low density of trees, high temperature whereas these authors carried out their studies in the well maintained peasant plantations. It is clear that the highest concentration of carbon appears where the value of trees' DBH is high. This matched with studies of [47] he conducted Average Tree Carbon (AGC; kg) rapidly increased with tree Diameter at Breast Height (DBH; in cm) among dominant tree species, this could be manifested by the number of trees in age 21 yrs and 35 yrs. At age 21 yrs the number of trees was high, but their DBH value was small, while the DBH value at age 47 yrs was high.

5. Conclusion

The study found different characteristics of trees per ha in the four aged groups. Trees aged 20 and 47 years were highest and lowest in number respectively, while the highest values of DBH and volume were found at the trees aged 47 years and hence, the highest and lowest values of the above-ground biomass were found at the trees aged 47 years and 16 years, accounting for 19.87 tons and 1.9 tons respectively. The soil organic carbon under the *A. senegal* plantations at all ages was fixed at the value of 0.1 t/h, and therefore, the total carbon stock in the El Demokeya forest is equal to 620.11 tons. Conclusively, the characteristics of trees, amount of aboveground biomass and carbon stock in the El Demokeya forest varied among the uneven-aged plantation groups. The study recommends and encourages farmers to introduce this species to their farms in order to contribute to their livelihood and actually climate change mitigation and environmental conservation. Further, farmers can get the financial benefits offered by the environmental services related to carbon sequestration in the carbon credit market through Clean Development Mechanism projects, which are the best option and a good opportunity to encourage the cultivation of *Acacia senegal* trees to increase income, protect the environment and face climate change.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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