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RESEARCH

Using Allometric Equation for Estimating Carbon Stock of Acacia senegal (Willd) Stands in Sheikan Reserved Forest, North Kordofan State, Sudan

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ABSTRACT

PURPOSE: The study aims to estimate the above-ground biomass (AGB) of Acacia senegal stands in Sheikan Reserved Forest, Sudan, using a combination of terrestrial inventory and remote sensing data, and to examine its relationship with tree growth parameters.

METHODOLOGY: A ground survey was conducted across 40 systematically distributed sample plots (0.09ha each), where tree measurements of diameter at breast height, height, and crown diameter were recorded. Normalized Difference Vegetation Index (NDVI) values were extracted from Landsat 8 imagery (2015) and analysed with field data using ERDAS and SPSS.

FINDINGS: The results revealed a significant relationship ($P = 0.02$) between NDVI and AGB of Acacia senegal stands. A linear regression model ($R^2 = 0.70$) using NDVI was selected for biomass estimation. Strong correlations were found between AGB and tree volume ($R^2 = 0.8$) and tree density ($R^2 = 0.9$). Maximum tree volume was 1.3m³/ha, maximum AGB 8.22t/ha, and total biomass 10.53t/ha.

VALUE: This study provides a practical NDVI-based model for estimating above-ground biomass of Acacia senegal stands.

KEYWORDS: *Acacia Senegal; Biomass; Kordofan; Modelling; Remote Sensing.*

INTRODUCTION

Sudan is endowed with diverse biological resources, representing both a key national asset and an important part of its cultural heritage. Based on the National Forest Inventory (FNI), the total area of Sudan has been classified into major classes with the following proportions: 15.85% forest, 13.24% other wooded land, 0.32% inland water, and 70.04% other land and desert (FNC and FAO, 2021). The rate of net forest loss has increased in Africa in each of the three decades since 1990. Africa experienced the greatest net loss of forest area during the decade to 2020, with the majority of the losses occurring in Eastern and Southern Africa, as well as Western and Central Africa. The average annual rate of net forest loss in Africa has increased since 1990, rising from 3.28 million hectares in 1990-2000 to 3.40 million hectares in 2000-2010, and further to 3.94 million hectares in the most recent decade (FAO, 2020). In 2015, the National Biodiversity Strategy and Action Plan (NBSAP) reported that forest cover accounts for a mere 11.9% of the country, with an annual deforestation rate exceeding 2.4% (Yasin *et al.*, 2023). Under the Republic of Sudan's Measuring, Reporting and Verification (MRV) System for REDD+, forest refers to land ≥0.5 ha (0.42ha, equivalent to a Sudanese feddan) with trees at least 2m tall and ≥10% canopy cover, excluding lands designated for agriculture or urban development (FNC, 2020).

Forests are vital sources of livelihood, providing for the population's needs as fuelwood and charcoal; these account for over 75% of the country's energy supply, as well as fodder for livestock and marketable products such as honey, gum arabic, tubers, and roots. In addition, forests play a crucial role in conservation, supporting biodiversity, offering environmental and climatic benefits, serving as wildlife habitats, and supplying medicinal plants for local communities (Adam *et al.*, 2023).

The National Forest Inventory (NFI) north of latitude 10°N, concluded in 1996, showed that the annual average growth of forests in Sudan was approximately 11.0 million m^3, which was far below the annual consumption rate of wood estimated by FNC and FAO (1994) to be about 16.0 million m^3 (FNC, 2020).

The density of gum arabic-producing trees varies across different regions. The primary production zones are located in the West and North Kordofan States. *Acacia senegal* Willdenow (Hashab) is recognised as producing the best quality gum arabic (Hammad *et al.*, 2025).

Between 1990 and 2005, Sudan's forests experienced significant degradation and deforestation, resulting in an estimated 12% loss, equivalent to approximately 8.8 million hectares. The majority of this deforestation occurred in the northern, eastern, and central regions of the country (Osman, 2021). Yasin *et al.* (2023) reported that Sudan's forest resources in drylands were influenced by human-induced (anthropogenic) and social and policy-related factors. These factors have led to overgrazing, the expansion of crop cultivation, unplanned harvesting, deforestation, and a decline in overall biodiversity. Furthermore, they have caused severe environmental degradation and accelerated desertification, compounded by insufficient information management for the planning and implementation of sustainable forestry initiatives

Biomass is the total mass of living biological material present in a given organism, population, or ecosystem at a specific time. It is usually expressed in terms of weight (dry or fresh) per unit area or volume (Begon *et al.*, 2006). Generally, biomass includes both above-ground and below-ground living and dead accumulation of trees, shrubs, vines, and roots. However, research on biomass estimation has focused on above-ground biomass (AGB)due to the complexity of measuring below-ground components. Consequently, various approaches and data sources have been employed to estimate forest AGB (Wang *et al.*, 2024; Elamin *et al.*, 2015).

Remote sensing is generally defined as the science and art of gathering information about an object, area, or phenomenon through the analysis of data acquired by a device without direct contact. This provides valuable information for monitoring and managing natural resources, assessing environmental changes, in fields of forestry, agriculture, urban planning, and disaster management (Adam *et al.*, 2023). The conventional method of biomass assessment relies heavily on field measurements; therefore, it is time-consuming, labour-intensive, and difficult to implement in remote areas (Elamin *et al.*, 2015).

The remote sensing technique is the most practical and cost-effective alternative for acquiring spatial and temporal data for various environmental uses. Also, it provides consistent, repeatable, and synoptic views of landscapes over large regions and long time periods (Chuvieco *et al.*, 2019).

SIGNIFICANCE OF THE STUDY

There is a gap in the database for the estimation of above-ground biomass in African forests, specifically in the small number of allometric equations for trees used by Chave *et al.* (2005) to develop general allometric equations for African forests. The contract between the Forest National Corporation (FNC) and Acacia Company aimed to invest in the Sheikan Reserved Forest for gum arabic production with plantations of Acacia senegal. This made Sheikan a unique forest in North Kordofan, as it was planted, planned, and managed by the private sector. The important question is what happens after the rent, and the environmental role of the forest. Accordingly, remote sensing and geographic information system (GIS) techniques have been proposed for integration with forest inventory to provide information that could help gather and restore data to manage the *Acacia senegal* plantations facing global issues.

RESEARCH JUSTIFICATIONS

There is a gap in accurate data on AGB for the forests in the Kordofan forest sector. Estimating trees' AGB was an important way to measure the energy potential of forests, obtaining accreted biomass equations for individual trees, predicting entire forest production and its relationship to stand density, comparing biomass across tree species, and assessing forest's fuel resource potential. In addition, the application of remote sensing and GIS in forest management saves time, gathers accurate data, and enables the analysis of the current status of the forests.

RESEARCH OBJECTIVES

The objective of this research is to assess the structural parameters of *Acacia senegal* trees in Sheikan Reserved Forest and examine their correlation with remote sensing measurements. It also aims to structure empirical correlations and functions for the estimation of *Acacia senegal* stands using remote sensing and GIS techniques.

LITERATURE REVIEW

Researchers emphasised the importance of forests and their role in addressing the global issue of climate change, as well as the growing interest in reducing carbon dioxide emissions. The availability of new planted forest and carbon stock data from the FRA 2020 enabled the analysis of the role of forests in generating and removing CO2 at the country, regional, and global levels. This indicates that the net contribution of forests to atmospheric carbon was very low, accounting for both emissions and removals on forested land (Tubiello *et al.*, 2021).

Losses (deforestation) or gains (afforestation and reforestation) of carbon are activities that are explicitly included in Article 3.3 of the Kyoto Protocol as “accountable activities” in the national commitments to reduce net greenhouse gas emissions since 1990 (United Nations Framework). In recent years, the focus on forest biomass as a source of sustainable energy has intensified, underscoring the growing significance of its precise quantification (UNFCCC, 2024).

While several authors have developed specific allometric equations for estimating forest biomass in China (Yang *et al.*, 2023), there is a limited awareness of the inventory of allometric equations in sub-Saharan Africa (SSA). Also, no attempt was made to estimate tree AGB for SSA, and they used existing and incomplete allometric equations (Henry *et al.*, 2011).

REDD+ (Reduced Emissions from Deforestation and Degradation), funded by the Forest Carbon Partnership Facility (FCPF), aims to mitigate greenhouse gas emissions from deforestation and forest degradation in developing countries. The programme also supports forest conservation, sustainable management, and enhancement of forest carbon stocks. Forest biomass, especially in tropical regions, is a key component of global biogeochemical cycles, which is directly related to the greenhouse effect (FNC, 2020).

Above-ground biomass in a forest is affected by a variety of factors such as on site (soil and moisture), climate variables (annual temperature, precipitation), or stand density and tree characteristics such as species and age and distribution of crown biomass. These all affect the carbon cycle, soil nutrient allocation, fuel accumulation, and wildlife habitat environments in terrestrial ecosystems, and it governs the potential of carbon emission due to deforestation (Gong *et al.*, 2023).

Santoro *et al.* (2021) reported that the global and national estimates of forest AGB stored in forests were produced by combining multiple satellite observations of synthetic aperture radar (SAR). The study also highlighted the importance of integrating remote sensing data to improve the spatial estimation of forest AGB, especially in regions with limited forest inventory capacity.

Forest inventory data serve as an important tool in global carbon cycle studies, offering the information necessary to enable large-area estimation of above-ground biomass. They also provide a basis for evaluating biomass estimates derived from methods such as eddy-flux covariance, remote sensing, and ecosystem modelling (Elamin *et al.*, 2015). Annual inventories include tree diameter at breast height (DBH) and, optionally, tree height to estimate AGB through specific allometric equations; this is an essential step in assessing carbon stocks (Yang *et al.*, 2023).

Effective climate change adaptation and mitigation depend on the significant contributions of plantations and natural forests. In savanna regions, extensive agricultural expansion has led to soil degradation, loss of biodiversity, and increased vulnerability to climate change (UNFCCC, 2024).

The Reduced Emissions from Deforestation and Degradation (REDD+) programme, is funded by FCPF. It is an initiative designed to reduce greenhouse gas emissions from deforestation and forest degradation in developing countries, while also promoting forest conservation, sustainable forest management, and enhancement of forest carbon stock. Biomass of forests, for example, plays a main role in tropical forests in global biogeochemical cycles, especially the carbon cycle and its relationship to the greenhouse effect; this has heightened interest in estimating the biomass density of tropical forests.

The allometric equations, that relate easily measurable tree dimensions (such as diameter at breast height and tree height) to biomass, are commonly used in forest ecology for estimating biomass and net primary productivity (NPP) in major planted forests. The developed equations are used for shrub and small tree species in subtropical China (Ali *et al.*, 2015).

Remotely sensed data were used to fill spatial and temporal gaps in forest inventory data, augment, and enhance estimates of forest AGB and carbon stocks. The advantages of using remotely sensed data for AGB estimation include the integration of multi-source data (remotely sensed data) within a GIS, making it possible to generate spatially accurate estimates of AGB over large areas (Tian *et al.*, 2024).

MATERIAL AND METHODS

Study Area Description

The study was conducted in Sheikan Plantation Reserved Forest in Sheikan locality, North Kordofan State, Sudan (Figure 1). The forest is located between latitudes 12°30′ and 12°36′ N and longitudes 29°36′ and 29°58′ E. In 1998, the Acacia Company planted the forest with *Acacia senegal* trees (4,550ha) for gum arabic production. The environment of the *Acacia senegal* stands is characterised as an homogenous forest with the same age, site, and morphology. The mean rainfall amount ranges from 250mm to 450mm per annum in summer, the minimum mean temperature is between 16°C-28°C, and the maximum temperature can rise as high as 45°C during the daytime (Adam *et al.*, 2023)

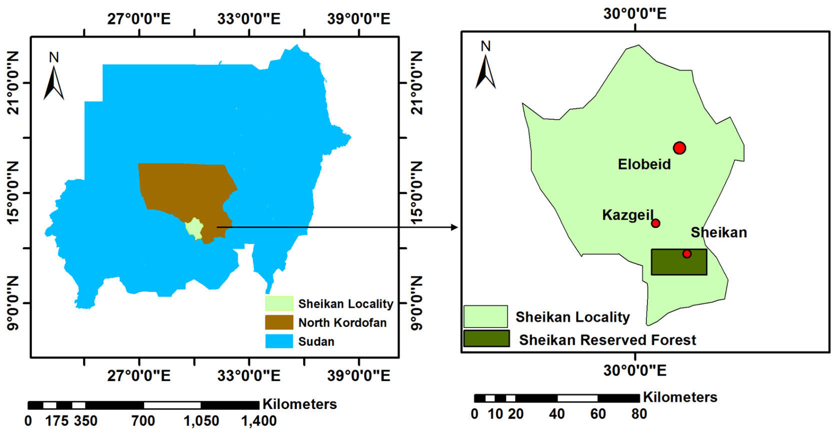

Figure 1: Location of the Study in Sheikan Reserved Forest

Source: Developed by author, 2025

Data Collection

The study is based on two sources of primary data; the first source is a field dataset from *Acacia senegal* trees. The inventory data were measured after a projected subset image with the boundary of the Sheikan forest was created. The second source consists of remote sensing data obtained from the Landsat 8 OLI (Operational Land Imager), collected on 2 May 2015 during the dry season. The image was pre-processed and processed, and the Normalized Difference Vegetation Index (NDVI) was extracted. The extracted values of these indices were integrated with field inventory data to create regression models for biomass (Figure 2).

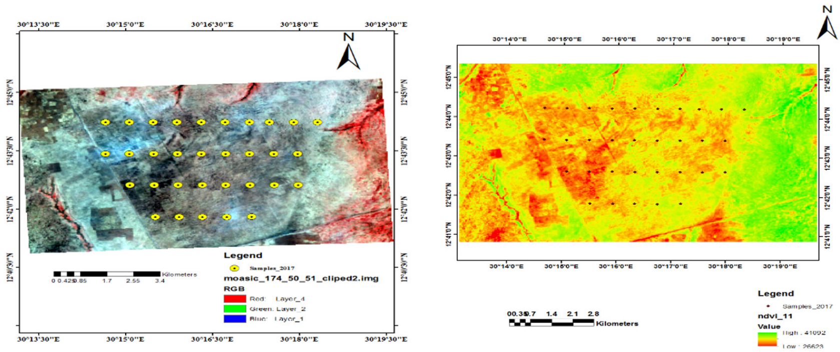

Figure 2: Location of the Sample Plots in Sheikan Reserved Forest on Landsat 8 OLI dated 2 May 2015

Source: Developed by the author using Landsat 8 OLI dated 2 May 2015

Field Survey

Four survey lines and 40 sample plots were systematically distributed with a spacing of 750 x 1,500m. The area of each sample plot is 0.09ha (30m*30m), which is equal to the pixel size of a Landsat 8 image. The co-ordinates were projected from the map with a GPS, using the WGS84 map datum and the UTM projection (Figure 2).

RESULTS

Biomass Calculation

For multi-stem trees, the quadratic mean diameter (DBHqm) was calculated using the equation conducted by (Mbow *et al.*, 2013).

$$DBH_{qm} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} DBH^2} \quad \text{.........................} \ (1)$$

where:

DBH_{qm} : is the average DBH size calculated using the multiple stems DBH1,2,…n of each individual trees

DBH: Diameter at breast height, N: Number of stems

The NDVI value (DN) was extracted and integrated with the calculated biomass of *Acacia senegal* trees using an allometric equation. Data were analysed using both SPSS and Excel programs. The study developed fitting equations using regression models (inverse, cubic, quadratic, power, logarithmic, linear, exponential, compound, and logistic), based on both ground and remotely sensed data.

REMOTE SENSING INDICATORS FOR BIOMASS ESTIMATION

The remote sensing indicator for biomass calculation is represented by the NDVI. Table 1 shows the average, maximum, minimum, standard deviation, and standard error of NDVI values extracted from the image.

Table 1: NDVI indicators used for biomass estimation

NDVI	*Item*
Average	0.07659
Minimum	0.06809
Maximum	0.08304
Standard Deviation	0.00072
Standard Error	0.00395

Source: Adapted and compiled by the author from a processed image of Landsat 8 2015

ACACIA SENEGAL TREES' PARAMETERS FOR BIOMASS ESTIMATION

Table 2 shows the estimated biomass from *Acacia senegal* tree parameters. These parameters are average number of trees (ha), average quadratic mean diameter (cm), the above-ground biomass (AGB) of *Acacia senegal* trees, the below-ground biomass (BGB) (tonne/ha), total biomass (TM) (tonne/ha), and carbon content (tonne/ha). The above-ground and below-ground biomass was calculated with the average diameter of *Acacia senegal* tree at 7.01cm. The average AGB, average BGB, total tree biomass (TB), and average carbon content were estimated as 0.277tonne/ha, 0.077tonne/ha, 0.354tonne/ha, and 0.177tonne/ha, respectively (Table 2). This result is in line with results obtained by Elamin *et al.* (2015) in Um Habila Reserved Forest, where *Acacia senegal* trees have an average diameter of 7.31cm. The above-ground tree biomass, below-ground tree biomass, and total tree biomass (TB) of *Acacia senegal* stands were found to be 0.015tonne/ha, 0.303tonne/ha, and 0.018tonne/ha, respectively. This variation in the amount of biomass is relevant to the difference in sample area (5m x 5m). The study found the estimated average tree volume (1.3m3/ha), maximum AGB (8.22t/ha), and total maximum biomass (10.53t/ha).

Table 2: Average Tree Attributes for Biomass and Carbon Content in Hectares in Sheikan Reserved Forest

Item	*n. of tree/ha*	*QDBH (cm)*	*Volume/ m^3*	*Above Biomass (tonne)*	*Below Biomass (tonne)*	*Total Biomass (tonne)*	*Carbon*
Max	656.00	12.50	3.44	8.226	2.303	10.529	5.264
Min	12.00	5.00	0.33	0.039	0.010	0.050	0.025
Average	233.00	7.01	1.33	0.277	0.077	0.354	0.177
SD	14.17	0.07	0.07	153.67	43.03	196.69	98.34
Standard error	2.59	2.81	0.01	28.06	7.86	35.91	17.97

Source: Adapted and compiled by the author from the collected field data

The results of the forest inventory showed that the present situation of Sheikan Reserved Forest has a low stocking density with 233 trees/ha (21 trees/0.09ha), while the ideal number considered to be 1,111 trees/ha, and the average volume of a mature tree is 1.3 m3/ha. Compared to another study in Nabag Reserved Forest, the average volume of a mature tree is equal to 0.068m3 (Mohamedain, 2009). He reported an average tree density of 118 trees per ha, and an average volume of 3.7m3 per ha; these are higher than those observed in this study, likely due to the planned sustainable management in the Nabag Reserved Forest.

MODELLING OF *ACACIA SENEGAL* TREES' BIOMASS

Among the checked models, the linear model proved the best fitting regression model for estimation of *Acacia senegal* tree biomass ($R^2 = 0.7$, P-value = 0.02); it showed the minimal standard error of the estimates (0.177) (equation 1 and Figure 3).

$$Y = a + a1x \quad \text{.................. equation 1}$$

Where:
Y = log biomass (Kg)
X=values
a = constant (56.4)
a1 = model coefficient (1.943)

As far as the BGB is concerned, 0.2 of the AGB was taken to estimate the BGB (Calvo Buendia *et al.*, 2019).

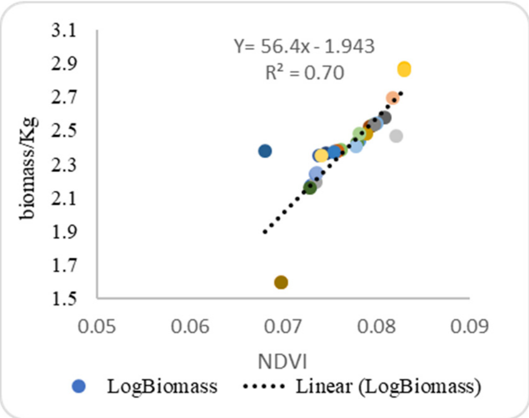

Figure 3: Linear Regression Curve for Estimation of *Acacia senegal* biomass
Source: Adapted and compiled by the author from the collected field data

RELATIONSHIP BETWEEN CALCULATED BIOMASS AND OTHER TREE PARAMETERS

The data were collected from a plantation area, and the stands are characterised as homogeneous in terms of age, soil condition, and growth habit. The correlations between AGB and tree density (trees per hectare) were examined. Also, correlations between NDVI and the individual tree volume and the tree density (trees per hectare) were developed. The correlations between the above-ground biomass and tree volume, as well as the number of trees, were found as R^2 values of 0.8 and 0.9, respectively (Figure 4). While the correlations between NDVI and tree volume and tree density were found with R2 values of 0.86 and 0.6, respectively (Figure 5).

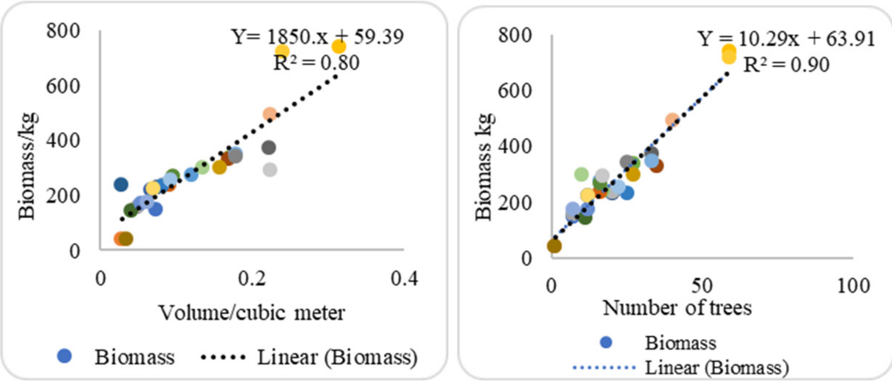

Figure 4: Linear Relationship between Biomass with Tree Volume, and Number of Trees

Source: Adapted and compiled by the author from the collected field data

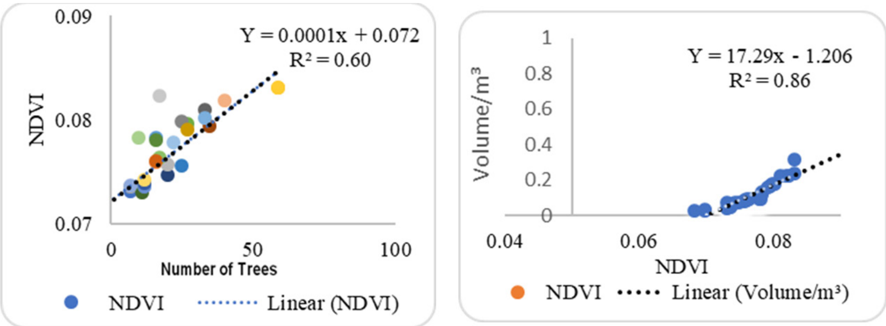

Figure 5: Linear Relationship between Biomass NDVI with Tree Volume and Number of Trees

Source: Adapted and compiled by the author from the collected field data

Research Value

As a result of this research, an integrated model combining ground-based measurements and NDVI values, with an R^2 of 0.70, was developed to estimate the above-ground biomass of *Acacia senegal* stands in Sheikan Reserved Forest, North Kordofan State, using NDVI data. The model is a set of fixed plantation stands, where the *Acacia senegal* tree is the pure stand in Sheikan Reserved Forest.

CONCLUSIONS

The study developed linear models for the estimation of biomass using NDVI, with NDVI providing the best relationship in the linear regression analysis, forming the primary conclusion of the modelling section. The proposed models were used to estimate the biomass of *Acacia senegal* stands and are intended for application by the Forest National Corporation (FNC), Acacia Company, and related organisations to evaluate the environmental attributes of *Acacia senegal* in Sheikan Reserved Forest. Being the main carbon sink in Kordofan's gum arabic belt, *Acacia senegal* significantly contributes to carbon sequestration and global climate mitigation efforts

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