



Estimation of Forest Biomass and Carbon Stocks Changes in Sunt (*Acacia nilotica* Linn Willd.) Plantations, Sinnar State, Sudan

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ABSTRACT

This study quantifies changes in tree density, above ground biomass (AGB) and above ground carbon (AGC) in Seiro Riverine Forests (SRF) and Abutiga Riverine Forest (ARF) we use inventory data done by forest national corporation (FNC) in 2006 and reinventors in 2015 for this research. A total of 224 circular sample plots (1000 m² each), 129 in Seiro and 96 in Abutiga, were established using a systematic sampling grid method. The distance between plots was 100 m, and between survey lines, 200 m. In each plot, all living trees were identified and counted, and their diameters at breast height (DBH) were recorded. The findings revealed a significant reduction in average tree density, dropping from 93 to 40 trees/ha in SRF, and from 140 to 40 trees/ha in ARF. (AGB) and (AGC) were assessed in *Acacia nilotica* plantations of varying ages in Abutiga and Seiro forests. Garef consistently showed the highest biomass and carbon stocks, Maya the lowest, and Karb intermediate values. Similar trends were observed across older and younger stands, highlighting strong site-specific differences. These results emphasize the importance of targeted management to sustain carbon storage and enhance the ecological function of *Acacia nilotica* plantations.

Keyword: Biomass, Carbon Stock, Forest Degradation, Sinnar State, Trees Density



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1. Introduction

Forest degradation is defined from various perspectives, depending on the interests and objectives of different programs, international conventions, and global policies addressing biodiversity, climate change, and forest management. The manifold negative impacts of forest degradation necessitate a comprehensive understanding and definition of this process [1]–[3]. Forest degradation refers to the reduction in the forest's capacity to provide goods and services due to human-induced disturbances [4]. This encompasses reductions in density, height, biomass, basal area, and diversity of woody communities [5], as well as the forest's ability to produce wood biomass, tree density, and regeneration [6].

Forest degradation affects ecosystems and local communities reliant on forests for various goods and services. The FAO (2011) estimated that the annual rate of forest degradation in Africa is nearly 50% of the annual deforestation rate, highlighting the need to monitor and quantify this process within the context of global carbon cycling [7]. Estimating aboveground biomass (AGB) in tropical forests is crucial for sustainable forest management and understanding forests' role in the global carbon cycle. Accurate AGB estimates are essential for determining changes in carbon storage within forest ecosystems, typically derived by applying a conversion factor to the AGB values [8].

In the past decade, the REDD+ program, under the United Nations Framework Convention on Climate Change, has emphasized reducing emissions from deforestation and degradation. This initiative promotes large-scale forest carbon inventories, encouraging developing countries to limit carbon emissions, manage forests sustainably, and sequester carbon stocks [9].

The Sunt (*Acacia nilotica* Linn Willd.) plantations, found in the Seiro and Abutiga Riverian forests, provide a unique opportunity to study the dynamics of biomass and carbon stocks in the context of forest degradation. *Acacia nilotica* is known for its ecological and economic importance, making it essential to understand how its biomass and carbon sequestration capacities change over time.

Therefore, the primary objective of this research is to estimate changes in tree biomass and carbon stocks as indicators of forest degradation in the Sunt plantations of the Seiro and Abutiga Riverian forests between 2006 and 2015. Specific goals include: (1) estimating the biomass and carbon stock of trees and assessing forest density for 2006 and 2015, and (2) systematically quantifying the dynamics and changes in biomass and carbon stock within these ecosystems over the specified timeframe. This study aims to provide valuable insights into the potential of Sunt plantations for carbon sequestration and inform strategies for mitigating climate change through forest management.

2. Materials and Methods

2.1. Study Area

The study area for this research is located in Sinnar State (Figure 1), chosen due to its strategic and ecological significance. Sinnar State is traversed by the Blue Nile, which plays a critical role in shaping the region's landscape and supporting its unique ecosystems. Along the banks of the Blue Nile are the Seiro and Abutiga Riverain Forest Reserves, selected as case studies for this research because they exemplify the typical characteristics of Riverain Forests found within the Nile basin. These forest reserves feature three key landscape components: the Maya, or basin bottom; the Garif slope, which is the slope closest to the river; and the Karab slope, which adjoins the inland clay plains [10]. The forests selected for study also represent a variety of age classes, providing valuable data for investigation. Sinnar State is in the central eastern part of Sudan. It shares borders with Gezira State to the north, White Nile State and South Sudan to the west, Gadarif State to the east, and Blue Nile State and Ethiopia to the south and southeast. The state lies in the rich savanna belt between latitudes 12.5° and 14.7° N, and longitudes 32.9° and 35.4° E [11] administratively, the state is divided into seven localities.

The Blue Nile River floodplain within Sinnar State is a significant ecological zone. It contains 182 forests of Sunt (*Acacia nilotica*), which alternate along both sides of the Blue Nile in a narrow, discontinuous strip [12]. These forests are vital for maintaining biodiversity and supporting local communities. For this research, the Seiro and Abutiga Forest Reserves were selected for detailed analysis. The Seiro Forest covers an area of approximately 234.78 hectares, while the Abutiga Forest spans 182.28 hectares, making them important examples of the region's riverain forest ecosystems. Figure 1 illustrates the location of these reserves within the broader landscape.

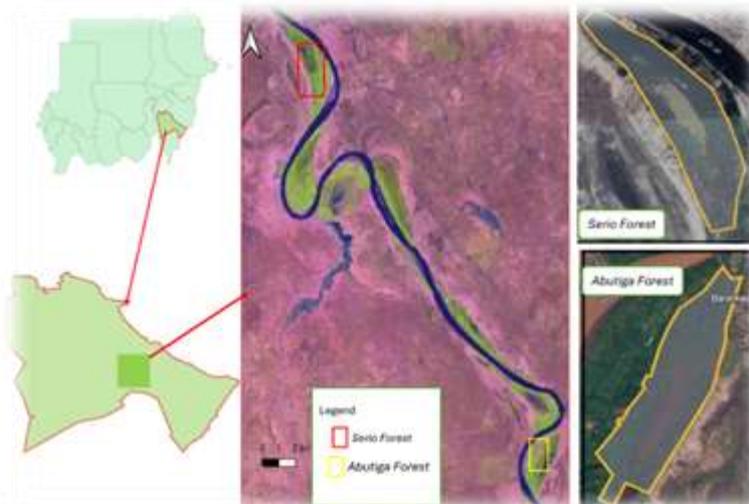


Figure 1. Study area

2.2. Data Collection and Sampling Design

Data collection for this study involved two distinct datasets. The first dataset, acquired in 2006, was sourced from the National Forest Corporation records in Sinnar State. In 2015, a comprehensive inventory was conducted to gather the second dataset, targeting the same locations and sample plots as the first dataset. This inventory focused on the Seiro and Abutiga Riverain forests. Measurements, such as Diameter at Breast Height (DBH), were taken using callipers, and tree heights were measured with a Haga altimeter. Additionally, a Global Positioning System (GPS) was used to precisely locate the sample plots. A total of 224 circular sample plots (1000 m² each), 129 in SFR and 96 in AFS, the consistent methodology between datasets allowed for a comparative analysis of vegetation characteristics over the specified time interval.

The data collection utilized a systematic sampling grid created with QGIS software. Parallel survey lines were spaced 200 meters apart, and circular plots were placed every 100 meters along each line (Figure 2). Each plot covered approximately 1,000 m² (radius = 17.84 m), resulting in a sampling intensity of 5%. Upon locating the plot centre, trees beyond the 17.84-meter radius were marked. Trees within the plot were marked at breast height (1.3 meters) and assigned unique identifiers. Relevant data, including tree characteristics and site types (Garif, Karab, Maya), were recorded on specially designed forms.

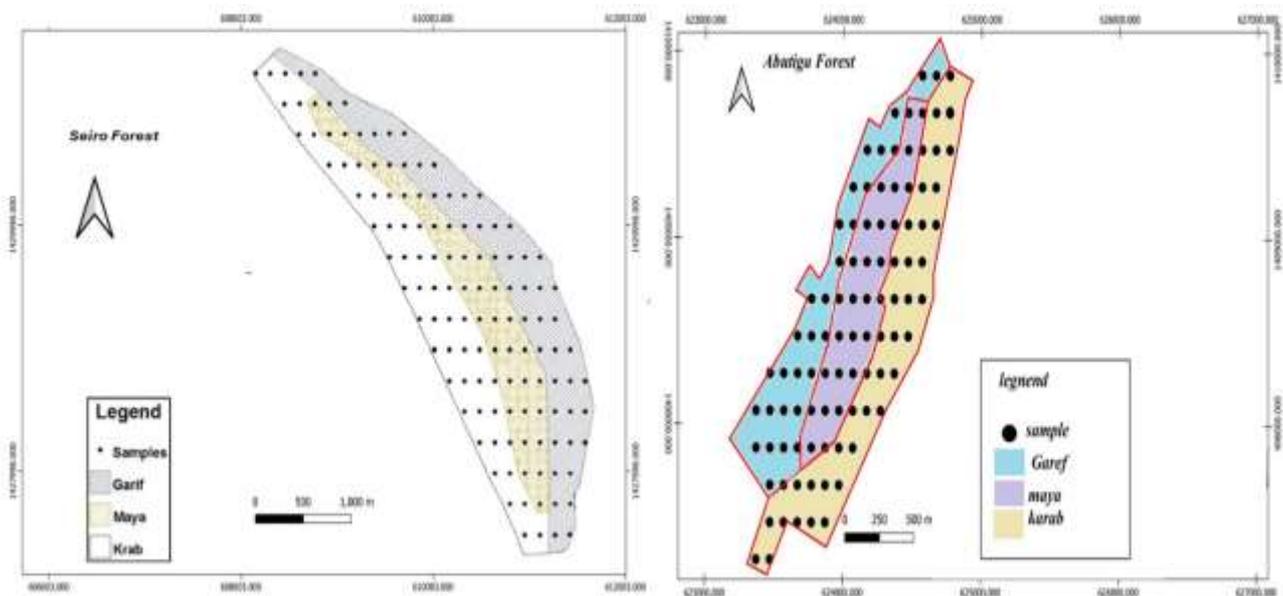


Figure 2. Distribution of sample plots in Seiro and Abutiga forest, Sinnar State, Sudan

2.3. Statistical Analyses

The collected data were processed and analysed using Microsoft Excel 2016. Aboveground woody biomass primarily consists of the stems and branches of trees. Since direct in situ biomass estimation is challenging, a non-destructive method was used to estimate the biomass of trees at different ages. This was done using allometric equations developed by Djomo et al. [13] for African tropical forests (Equation 1). In addition, the carbon stock of each tree was obtained by multiplying the estimated dry biomass by the percentage carbon content (PCC) (Equation 2). Applied in this study was 0.5, as recommended by the Intergovernmental Panel on Climate Change (2006) [14]. This PCC value has been commonly used to estimate carbon stocks in African forests [15]-[17].

$$\ln(M) = -0.841 + 2.082 \ln(D) + 1.248 \ln(\rho) \quad (1)$$

$$C = M \times PCC \quad (2)$$

Where M is dry weight biomass (kg), D is the diameter at breast height (cm), ρ is wood density (g/cm³), C is carbon stock (kg), and PCC is a percentage carbon content. The value of wood density for *Acacia nilotica* was 0.86 g/cm³ [18]. Aboveground biomass and carbon stock estimates were calculated as mean \pm standard deviation (SD) to provide interval estimates, allowing for a more accurate representation of variability and the reliability of the sampling results.

3. Results and Discussion

3.1. The Status of Forests Density

The forest inventory data from 2006 and 2015 revealed a significant decrease in tree density per hectare in both Seiro Forest and Abutiga Forest Reserve, highlighting a worrying trend in forest cover reduction. Table 1 presents tree densities across three site classes: Garif, Maya, and Karab. In Seiro Forest, the density plummeted from 100, 80, and 100 trees per hectare in 2006 to just 50, 30, and 40 trees per hectare in 2015 for the respective site classes. Abutiga Forest Reserve also experienced declines, with densities dropping from 140, 150, and 110 trees per hectare in 2006 to 40, 60, and 30 trees per hectare in 2015.

This sharp decrease in tree density reflects a substantial loss of forest cover, which may be indicative of poor management practices such as over-thinning or illegal logging. According to Harrison [19], after 20 years, the density of *Acacia nilotica* forests should be maintained between 100 and 125 trees per hectare with proper thinning practices. In contrast, both reserves were managed far below these guidelines during the study period.

Seiro Forest Reserve showed particularly severe degradation. Initially at adequate levels at age 12, densities were below the prescribed minimum of 200 trees per hectare by age 21, dropping to densities of 50, 30, and 40 trees per hectare - far below the expected 125 trees per hectare based on Harrison's thinning schedule. In contrast, Abutiga Forest Reserve had initially higher densities at age 13, but these too were not sustained, declining sharply by age 22 to well below optimal levels.

These patterns of decline in both reserves suggest significant mismanagement, potentially due to excessive thinning or illegal activities by nearby communities. This observation aligns with Osman [20] who reported similar findings in the Lembwa Forest, located in the Blue Nile region, where heavy thinning had also been observed. This trend points to a broader issue of forest management practices that fail to sustain forest ecosystems, necessitating a re-evaluation of conservation strategies and enforcement measures to prevent further degradation.

The forest inventory data collected in 2006 and 2015 from Seiro Forest and Abutiga Forest Reserve highlight a significant decrease in tree densities per hectare, indicating a worrying trend in forest cover reduction over the nine-year period. This data, presented in Table 1, documents tree densities across three distinct site classes: Garif, Maya, and Karab. Specifically, in Seiro Forest, densities fell from 100, 80, and 100 trees per hectare in 2006 to 50, 30, and 40 trees per hectare in 2015, respectively. In Abutiga Forest Reserve, similar declines were observed, with densities decreasing from 140, 150, and 110 trees per hectare in 2006 to 40, 60, and 30 trees per hectare in 2015.

This marked decline not only underscores a loss of forest cover but also suggests potentially inadequate forest management practices, such as over-thinning or illegal logging. According to guidelines by Harrison [19], the density of *Acacia nilotica* forests, after 20 years, should be maintained between 100 and 125 trees per hectare with a proper thinning regime. However, the observed data from both reserves indicate a significant deviation from these recommendations, pointing to mismanagement.

In the case of Seiro Forest Reserve, the degradation was particularly severe. At age 12, the tree densities were already below the levels prescribed for sustainable growth, which should have been at least 200 trees per hectare. By the time the forest reached 21 years, this mismanagement led to a drastic reduction in tree density to 50, 30, and 40 trees per hectare—well below the approximately 125 trees per hectare that Harrison's guidelines would suggest for a well-managed forest.

Similarly, Abutiga Forest Reserve exhibited an inability to maintain healthy forest densities despite initially higher figures at age 13—140 and 150 trees per hectare in Garif and Maya, respectively, and 110 in Karab. By age 22, these figures had plummeted to 40, 50, and 30 trees per hectare, respectively. This sharp decline is indicative of severe mismanagement and raises concerns about the long-term viability and sustainability of these forests.

The patterns observed in both reserves suggest a broader issue of forest mismanagement. Potential contributing factors to this decline could include a lack of enforcement of sustainable forestry practices, insufficient monitoring of forest health, and pressures from nearby communities who may engage in illegal cutting for firewood or land clearing for agriculture. These practices echo findings by Osman [20] in the Lembwa Forest of the Blue Nile region, where heavy thinning was also noted.

The case studies of Seiro and Abutiga Forest Reserves emphasize the urgent need for a comprehensive overhaul of forest management policies. Effective enforcement mechanisms are crucial to ensure adherence to sustainable management guidelines. Moreover, involving local communities in forest conservation efforts is imperative. Providing alternative livelihood options and educating these communities on the benefits of sustainable forest management could help mitigate the adverse effects of human activities on forest reserves.

An integrated approach involving stricter regulatory oversight, community engagement, and the adoption of scientifically backed forest management strategies is essential for the rehabilitation and sustainable management of these forest ecosystems. Ensuring the survival of these forests for future generations requires a committed and multifaceted response that addresses both the ecological and socio-economic factors contributing to forest degradation. This holistic approach is key to reversing the trends observed and promoting the recovery of forest areas impacted by previous mismanagement.

Table 1. Average above ground biomass and carbon stock per tree

Inventory period	Site Class	DBH (cm)	Tree density/ha
Seiro 2015	Garef	35.3	50
	Maya	15	30
	Karab	31	40
Seiro 2006	Garef	24.5	100
	Maya	20	80
	Karab	21	100
Abutiga 2015	Garef	25	40
	Maya	25	50
	Karab	16.4	30
Abutiga 2006	Garef	19.5	140
	Maya	15.3	150
	Karab	10.3	50

3.2. Aboveground Biomass and Carbon Stock

The distribution of aboveground biomass (AGB) and aboveground carbon (AGC) varied across sites, forest reserves, and age classes (Table 2). In the 22-year-old Abutiga forest, Garef exhibited the highest mean AGB ($81.5 \pm 49.5 \text{ mg ha}^{-1}$) and AGC ($40.8 \pm 24.9 \text{ mg C ha}^{-1}$), with values ranging from $7.7\text{--}223.6 \text{ mg ha}^{-1}$ and $3.8\text{--}111.8 \text{ mg C ha}^{-1}$, respectively. Maya showed intermediate averages ($15.8 \pm 9.1 \text{ mg ha}^{-1}$ and $7.9 \pm 4.6 \text{ mg C ha}^{-1}$), while Karab recorded the lowest ($3.7 \pm 1.9 \text{ mg ha}^{-1}$ and $1.9 \pm 0.9 \text{ mg C ha}^{-1}$). In the 21-year-old Seiro forest, Garef also maintained the highest mean biomass ($31.7 \pm 19.1 \text{ mg ha}^{-1}$) and carbon stock ($15.8 \pm 9.6 \text{ mg C ha}^{-1}$), followed by Karab ($19.0 \pm 9.1 \text{ mg ha}^{-1}$ and $9.5 \pm 4.6 \text{ mg C ha}^{-1}$). Maya consistently exhibited the lowest averages ($3.1 \pm 1.7 \text{ mg ha}^{-1}$ and $1.6 \pm \text{SD mg C ha}^{-1}$).

Similar trends were observed in younger stands. In the 13-year-old Abutiga forest, mean AGB ranged from $6.1 \pm 2.9 \text{ mg ha}^{-1}$ in Karab to $25.8 \pm 13.4 \text{ mg ha}^{-1}$ in Garef, corresponding to AGC values of $3.1\text{--}12.9 \text{ mg C ha}^{-1}$. In the 12-year-old Seiro forest, Garef again exhibited higher mean AGB ($28.2 \pm 13.3 \text{ mg ha}^{-1}$) and AGC ($14.1 \pm 6.8 \text{ mg C ha}^{-1}$) compared to Maya ($15.0 \pm 5.6 \text{ mg ha}^{-1}$ and $7.5 \pm 2.8 \text{ mg C ha}^{-1}$) and Karab ($18.3 \pm 5.7 \text{ mg ha}^{-1}$ and $9.1 \pm 5.7 \text{ mg C ha}^{-1}$).

Above ground biomass and carbon stock at old age was lower than 2006 inventory period in tow site classes. In the highly decreased than 50% in maya site in Seiro forest less so Abutiga forest in Garef site. This may be due to illegal cutting or over thinning reduced the average trees density. in contrast there an increase in biomass and carbon in four sites class Maya and Karab sites in Abu Taiga Forest and Garef and Karab in serio forest. however, the highest average biomass recorded in the Garef site class was 28.4 tons per hectare was lower when compared to Sudan average biomass of 55.98 tons per hectare [21].

The distribution of aboveground biomass and carbon stocks is strongly shaped by site quality and tree age, both of which showed significant variation between the Karab and Garef sites. However, these stocks remain vulnerable to dynamic environmental pressures and intensive utilization by local communities, such patterns align with previous studies that have documented the combined effects of site conditions and anthropogenic pressures on forest carbon dynamics [12], [22], [23].

Table 2. Tree age, average aboveground biomass (AGB), and aboveground carbon (AGC) of *Acacia nilotica* calculated per hectare in the two selected riverine forest reserves. Values represent site-level means derived from field measurements across the study periods.

Forest	Age (yr)	Site	Number of plots	AGB (mg ha ⁻¹)			AGC (mg ha ⁻¹)		
				Range	SD	Average	Range	SD	Average
Abutiga	22	Garef	48	7.7-223.6	49.5	81.5	3.8-111.8	24.7	40.8
		Maya	32	4.8-37.3	9.1	15.8	2.4-18.6	4.6	7.9
		Karb	49	1.7-12.3	1.9	3.7	0.9-6.2	0.9	1.9
Seiro	21	Garef	30	28.8-34.6	19.1	31.7	14.41-17.3	9.6	15.8
		Maya	27	2.9-3.3	1.7	3.1	1.4-1.7	0.85	1.6
		Karb	39	17.3-20.7	9.1	19	8.6-10.3	4.6	9.5
Abutiga	13	Garef	48	9.8-60.3	13.4	25.8	4.9-30.1	6.9	12.9
		Maya	32	6.4-25.2	5.3	16.2	3.2-12.6	2.8	8.1
		Karb	49	2.3-15.7	2.9	6.1	1.1-7.9	1.45	3.1
Seiro	12	Garef	30	26.3-30.2	13.3	28.2	13.11-15.1	6.8	14.1
		Maya	27	14.0-16.0	5.6	15	7.0-8	2.8	7.5
		Karb	39	17.1-19.4	5.7	18.3	8.5-9.7	5.7	9.1

AGB and AGC trends observed in Karab, Maya, and Garef plantations fall within the broader range of carbon stock values reported for *Acacia* forests in Sudan. Abaker et al. [24], for instance, documented aboveground carbon stocks of 5.55 mg ha⁻¹ in 7-year-old stands, 4.70 mg ha⁻¹ in 15-year-old stands, 6.89 mg ha⁻¹ in 20-year-old stands, and 5.20 mg ha⁻¹ in 24-year-old stands in El Demokeya Forest Reserve and El Hemaira Forest. When compared to these benchmarks, the results from this study indicate that Karab (3.1 mg ha⁻¹) is considerably lower than the values reported by Abaker et al. [24] pointing to severe degradation and loss of carbon storage capacity. Maya (15.8 mg ha⁻¹) is substantially higher than the reported range, suggesting relatively higher productivity and carbon accumulation than many other *Acacia* stands of similar age or condition. Garef site far exceeds the values from El Demokeya and El Hemaira, reflecting exceptionally high growth and productivity, likely supported by favourable site conditions, effective management, or both.

This comparison highlights the heterogeneous performance of *Acacia nilotica* plantations in Blue Nile (Figure 3). The decline in Karab suggests urgent intervention is needed to restore biomass and carbon sequestration functions, while Maya appears relatively stable but still vulnerable to ongoing pressures. The sharp increase in Garef demonstrates the potential of *A. nilotica* plantations to act as significant carbon sinks when protected and well managed. By situating these findings within the broader range of carbon stock studies in Sudan, it becomes evident that site-specific management and ecological factors strongly shape the success or decline of plantation systems.

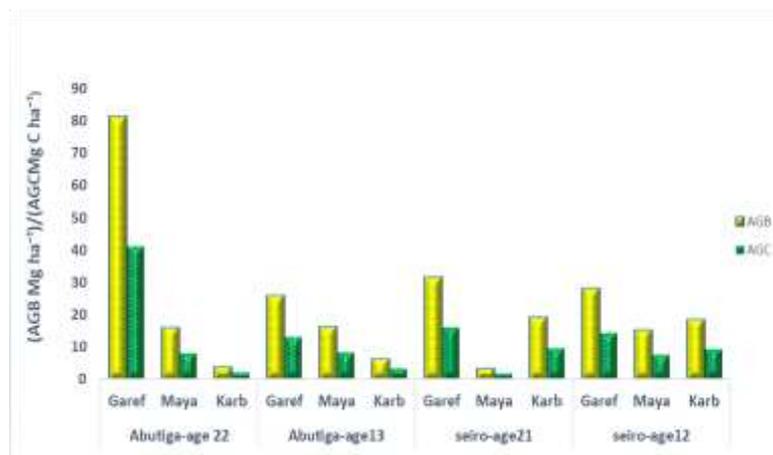


Figure 3. Aboveground biomass (AGB, mg ha⁻¹) and aboveground carbon stock (AGC, mg C ha⁻¹) across sites (Garef, Maya, Karb) within Abutiga and Seiro Forest Reserves for 2006 and 2015.

Overall, Garef sites consistently exhibited the highest AGB and AGC values compared to Maya and Karb, reflecting greater tree density and structural development. In contrast, Maya and Karb sites showed relatively lower biomass and carbon storage, with only modest increases over time. The observed differences highlight spatial heterogeneity and temporal dynamics in forest productivity and carbon sequestration potential across site classes.

4. Conclusions

This study in the Seiro and Abutiga Sunt (*Acacia nilotica*) plantations revealed the changes in tree density, biomass, and carbon stocks between 2006 and 2015, highlighting their role as indicators of forest degradation and regrowth. The decline in tree density reflects the impact of unsustainable harvesting and weak management, while the increase in biomass and carbon stock per unit area in some sites suggests that remaining trees have gained more biomass, partly compensating for the reduced stand density. These patterns illustrate the dual dynamics shaping plantation systems: degradation caused by over-thinning, grazing, or illegal logging on one side, and natural regrowth or effective management on the other. Strengthening sustainable management practices in Sunt plantations is therefore essential for balancing forest productivity with carbon sequestration, enhancing ecosystem services, and contributing to climate change mitigation. In line with the broader themes of land cover change and community-based forest management, the findings underscore the need to integrate plantation monitoring with participatory approaches. Promoting sustainable use and community engagement in managing *Acacia nilotica* plantations will help maintain carbon storage, support local livelihoods, and ensure the long-term sustainability of forest resources in Blue Nile.

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