Assessing Above-Ground Biomass for Carbon Credit Generation in Sawago Forest Reserve, Mbeya–Tanzania

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Abstract

This study aimed to assess Above-Ground Biomass (AGB) in Sawago Forest Reserve to facilitate carbon credit generation. The specific objectives were quantifying AGB, determining Above-Ground Carbon (AGC) storage, and estimating potential carbon credits. A systematic sampling approach was employed involving measurements of tree Diameter at Breast Height (DBH) in 46 sample plots. Allometric model was applied to estimate the AGB from DBH measurements. QGIS with the aid of the Avenza was used to layout plots. Plots were navigated and located using GPS receiver in the field. Microsoft Excel was used to compute AGB, AGC and carbon credits, and visualization. The results revealed an average density of 349.86 stems per hectare indicating a well-structured forest ecosystem. The AGB was 148,017.6 kg per ha translating a significant carbon storage which is crucial for climate change mitigation. The AGC was 69.568 tons per ha which was contributed by trees with greater DBH classes. Carbon credits was 255.08 CO_2e per ha on average which was contributed to a large extend by larger valuable trees with DBH greater than 55 cm. This amount of carbon credits per ha demonstrating the forest economic potential through carbon trading schemes. Sawago Forest Reserve holds substantial AGB, AGC storage and potential carbon credits making this forest reserve a viable candidate for carbon credit initiatives. The findings support the implementation of sustainable forest management practices and community-based conservation programs to enhance both ecological and economic benefits.

Keywords: Above-Ground Biomass, Above-Ground Carbon, Carbon Credits

1. INTRODUCTION

Forests play a vital role in mitigating climate change by acting as substantial carbon sinks, absorbing and storing atmospheric carbon dioxide [9]. Among the critical components of forest ecosystems, Above-Ground Biomass (AGB) serves as a significant reservoir for carbon sequestration [22]. Mugasha et al. [25] reported that the quantification of Above-Ground Biomass not only aids in understanding the carbon dynamics of a particular forest but also provides a foundation for climate change mitigation strategies, including carbon credit generation. Araya and Hofstad [2] revealed that there has been a growing global emphasis on mitigating climate change through various strategies including the use of carbon credit programs. Carbon credits are a form of tradable permits that allow organizations to offset their greenhouse gas emissions by investing in projects that reduce or capture an equivalent amount of emissions [1].

According to van der Gaast et al. [37] and van Kooten and Johnston [39] carbon credits are a measure of the reduction, avoidance, or sequestration of carbon dioxide emissions, and they can be traded in carbon markets. According to Anukwonke and Abazu [1] the mounting global threat of climate change underscores the importance of initiatives that mitigate greenhouse gas emissions, particularly carbon dioxide (CO_2). One such mechanism is the generation of carbon credits, which incentivize activities that reduce emissions or enhance carbon sequestration [8]. Carbon credits, often traded in international markets, provide financial incentives for sustainable land-use practices, afforestation, and reforestation efforts [30]. The assessment of AGB is a fundamental step in quantifying the carbon storage potential of a forest ecosystem and is pivotal for generating carbon credits [16]. In a well-conserved forest ecosystem, Above-Ground Biomass may vary depending on the status of the conserved vegetation [14]. Forests can accumulate large amount of Above-Ground Biomass in the form of trees, vegetation, and other plant matter [15]. Companies or entities that exceed their carbon emissions limits can purchase credits to offset their own emissions [38].

Forest conservation and sustainable management, particularly in areas like the Rungwe Nature Forest Reserve (RNFR), have emerged as key contributors to carbon credit initiatives [37]. Despite the ecological importance of the Rungwe Nature Forest Reserve, there is a pressing need for comprehensive and up-to-date data on the Above-Ground Biomass within the reserve [11]. Lack of accurate measurements poses a challenge to the effective participation of the reserve in carbon credit programs, this gap not only limits the potential financial resources available for conservation efforts but also hinders the reserve ability to highlight its contribution to global climate change mitigation [18]. Accurate and reliable data on biomass, facilitating the reserve active engagement in carbon credit initiatives [18]. In order to address these challenges, this study aimed to conduct an assessment of Above-Ground Biomass for Carbon Credits generation in the Sawago Forest Reserve within Rungwe Nature Forest Reserve in order to attract investment for enhancing forest conservation. Therefore, this study not only contributes to sustainable management of the Rungwe Nature Forest Reserve but also serves as a prototype model for effective carbon projects in similar forest ecosystems in Tanzania.

2. Materials and Methods

2.1 Study area description

2.1.1 Location

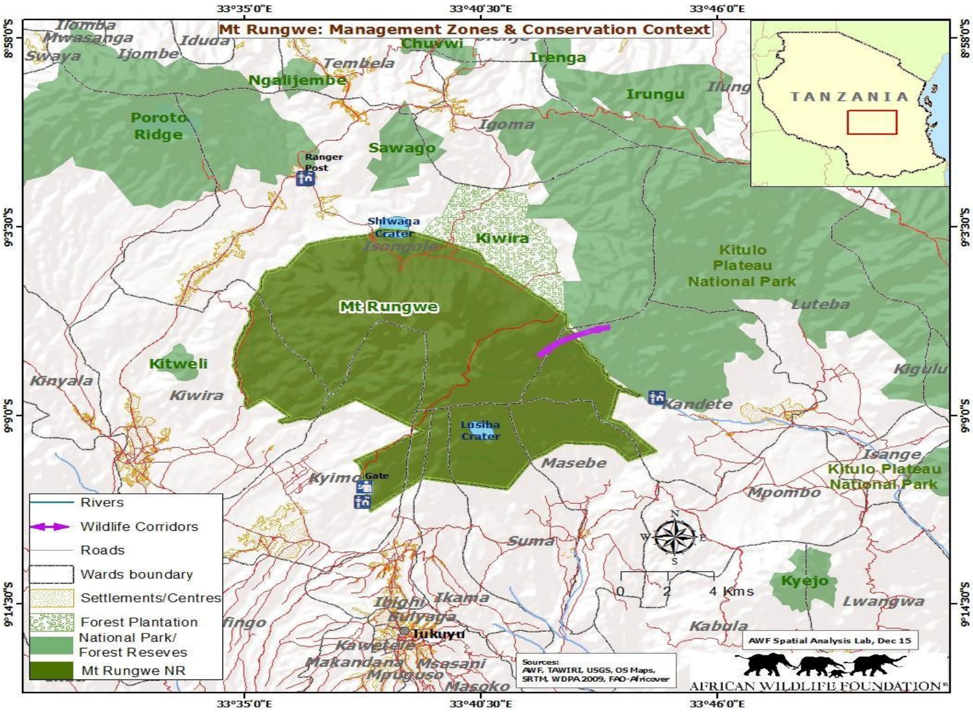
The study was conducted in Sawago FR which is the smallest reserve among the forests that constitute RNFR. It covers an area of 818 ha with a boundary length of 14.16 km and it is located between longitude $8^0$59' – $9^0$05' S and Latitude $33^0$3' – $33^0$40' E on a hilly terrain with steep valleys and a few flat areas at 1,704 – 2,354 m a.s.l. The forest is about 23 km South East of Mbeya City and 30 km North of Tukuyu. The Sawago FR is on the eastern side of Poroto Mountains south of Igoma village on the Mbeya – Isyonje/Kitulo road. From Mbeya City the road is easily accessed through Uyole – Tukuyu road to Isyonje. Also, the forest reserve border runs from Isyonje through Mbeya – Makete road to Njiapanda, Ngoha, Igoma and Kiwira Forest Plantation near Mwansazi village (Figure 1) [32].

2.1.2 Climate

The forest reserve climate which also applies to RNFR is significantly determined by the topographical landscape particularly in terms of annual and seasonal rainfall and temperature regimes [32]. The rainy season normally is from November to May while the dry season starts from June and ends in October. In the surrounding lowlands, rainfall ranges between 900 mm in the lowlands to 2700 mm in the highlands.

Exceptionally, the South Eastern slopes of the mountains receive up to 3000 mm of rainfall a year, the highest amount of rainfall in Tanzania [32]. The general range of temperature in the forest reserve area is between -6 °C in the highlands and 29 °C in the lowlands. The area enjoys abundant and reliable convectional rainfall with continental/convectional temperatures which stimulate abundant agriculture on the rich volcanic soils. The cool climate which is combined with high rainfall and humidity provide conducive environmental factors that enhance vigorous growth of vegetation and trees [32].

Figure 1: Geographical Map of RNFR



2.2 Sampling design and sample size

Systematic sampling design was employed in this study whereby the first plot was established randomly from any point of the forest reserve. Circular plots were preferable because they were easy to implement in the field and determination of trees inside the plot was less problematic than square plots [33]. In a very dense vegetation, stands with large numbers of small diameter stems, and uniform distribution of large stems the plot radius of 5.65 m with plot size of 100 m^2 are recommended while in a moderate sparse woody vegetation the radius of 12.62 m with plot size of 500 m^2 are recommended and for sparse wood vegetation 14.56 m with plot size of 665.7 m^2 are also recommended [34]. The nature of Sawago FR was sparse woody vegetation, therefore in order to capture many trees in a plot, the radius of 15 m with plot size of 706.5 m^2 were used. Sampling intensity was 0.4%.

The number of plots was determined used equation 1 [11].

$$n = \frac{TFA \times Si}{Ps \times 100} \qquad (1)$$

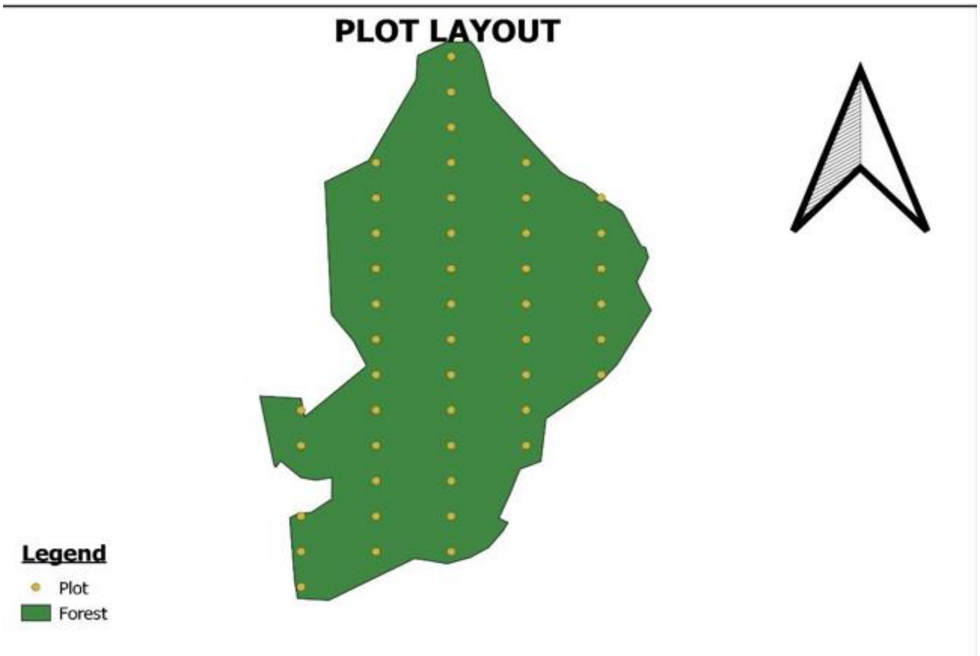
Where; n = Number of plots, TFA = Total Forest Area (Ha), Si = Sampling intensity (%) and PS = Plot Size (Ha).

The distance between plots was determined using equation 2 [11].

$$D = \sqrt{\left(\frac{TFA \times 10000}{n}\right)} \qquad (2)$$

Where; D = Distance between plots (m), TFA = Total Forest Area (Ha) and n = Number of plots
Based on RFNR management plan data of 2022, the total forest area of Sawago FR is 818 ha, 46 sample plots were used for this study. The distance between plots and transect distance were 421.69 m and 843.39 m respectively. Plots were laid out using QGIS with the aid of Avenza phone application to enable accurate placement of the plots. Plots were located in the field using GPS receiver Trees within the plot were marked by paint after its diameter measured and recorded to avoid the over count or undercounts of trees.

Figure 2: Layout of Plots in the Field



2.3 Data collection

Tree Diameter at Breast Height (DBH) was measured at 1.3 m above the ground. Bajracharya [3] revealed that small trees <5 cm DBH has relatively small quantity of biomass, therefore small trees <5cm DBH were not included in this study. Trees DBH was categorized in terms of diameter class as follow: 05 – 15 cm, 16 – 25 cm, 26 – 35 cm, 36 – 45 cm, 46 – 55 cm, and >55 cm. The DBH of each tree with the category above was measured using a caliper.

2.4 Data analysis

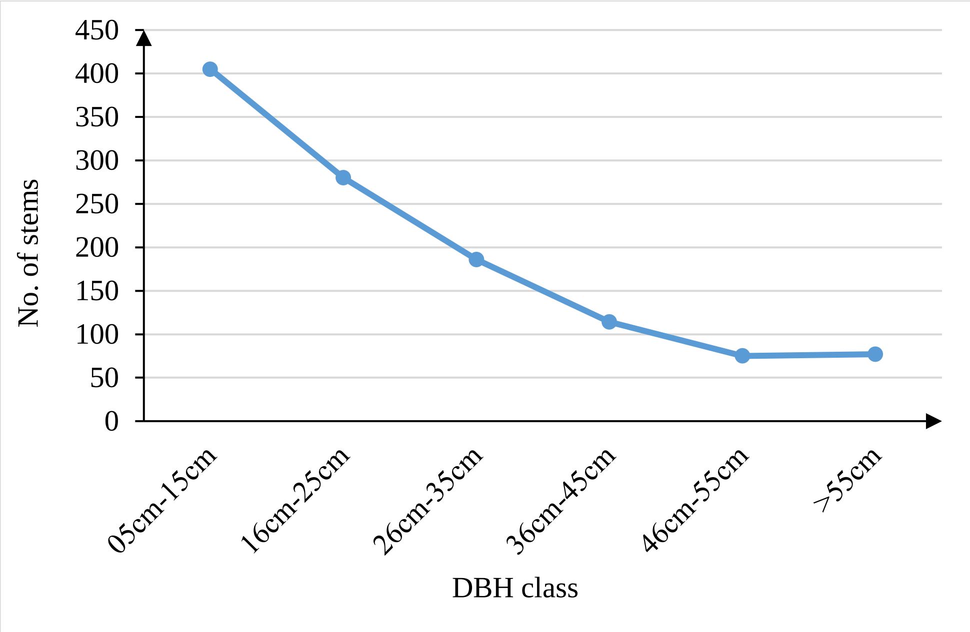
Microsoft Excel was used for computations and visualization. In Tanzania, AGB allometric models developed by Chamshama et al. [5] using DBH as the only independent variable and Malimbwi et al. [20] using DBH and tree height as independent variables have been used to estimate AGB. AGB model, AGB (kg) = $0.0625 \times DBH^{2.553}$ developed by Chamshama et al. [5] using DBH as the only independent variable was adopted for this study. The main reason for adopting the model with DBH as the only independent variable was due to time and financial constraints for measuring tree height in a natural forest.
Above-Ground Carbon (AGC) was computed using an allometric model Carbon = AGB (kg) × 47% developed by Mugasha et al. [25]. The equivalent amount of carbon dioxide (CO_2) captured by each tree was computed using the ratio of CO_2 molecular weight to the molecular weight of Carbon (C). Carbon credits were computed using the equivalent amount of CO_2 multiplied by the estimated AGC of each tree within a plot.

3. Results and Discussion

3.1 Tree density

A total number of 1137 stems in 46 sample plots with an area of 0.07065ha were measured as the representative of the whole population in Sawago FR. The average number of stems per hectare was 349.86. This indicates a moderate tree density across the forest. The results show that the distribution of tree stems across different DBH classes within Sawago FR were decreasing as the DBH class increased (Figure 3). This indicates a significant population of young or small trees within the forest.

Figure 3: Distribution of Stems per DBH Class



In the smallest DBH class 05 – 15 cm, the number of stems was the highest, with over 400 stems recorded. This resemble to findings of the study conducted by Löf et al. [17] which revealed that smaller trees are essential in forest regeneration and future growth. Their high numbers suggest a robust recruitment rate for the forest's long-term sustainability and ecological balance [6]. As the DBH classes increased from 26 – 35 cm, there was a notable decline in the number of stems dropping to approximately 200. This decline reflects the natural thinning process within the forest, where competition for resources such as light, water, and nutrients leads to the survival of only the more competitive and resilient trees. This determines which trees will continue to grow and contribute significantly to biomass and carbon storage [42].

The decline in the number of stems continues more sharply in the 36 – 45 cm and 46 – 55 cm DBH classes, with the number of stems falling below 150 and then to around 50 respectively. This sharp decrease indicates that few trees reach larger sizes which is typical in many forests where only a small fraction of trees grow to become large. According to Wasserman et al. [42] larger trees are crucial for the forest structural complexity and ecological functions such as providing habitats and contributing significantly to biomass.

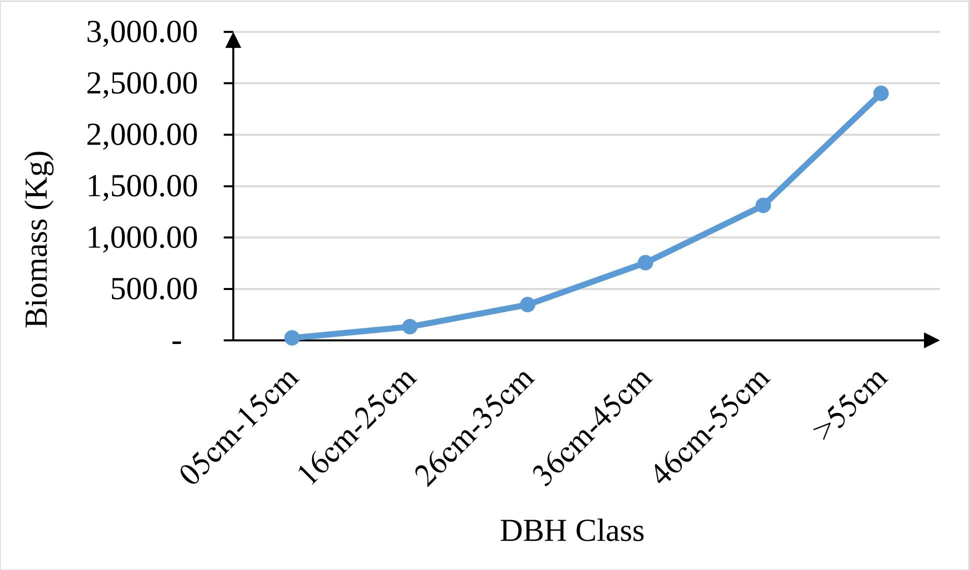
In the largest DBH class >55 cm the number of stems stabilizes at a low level of less than 50 stems. This small number of large trees underscores their ecological importance despite their scarcity. This aligns with Wasserman et al. [42] who assert that the largest trees in a forest act as keystone structures that support diverse wildlife and store substantial amounts of carbon. The presence of these large trees indicates a wellestablished forest capable of supporting long-term ecological processes and a high amount of biomass. The distribution of stems across DBH classes, combined with the total and average stems, highlights the forest's dynamic structure. It suggests a healthy recruitment of young trees, a natural thinning process, and the presence of mature trees that contribute to ecological stability and resilience [4].

3.2 Above-Ground Biomass (AGB)

The findings show that AGB was 148,017.6 kg per ha resulting to 121,078,412.46 kg for the total forest area of 818 ha (Appendix 2). The most popular measurable parameter for estimating AGB is DBH in cm and height in meter [25]. In this study, DBH in cm was used as the only measurable parameter within a forest. This aligns with the study conducted by Fotis et al. [7] in which DBH was used as the measurable parameter for estimating AGB. The link between DBH and AGB is a fundamental aspect of forest ecology and management [10]. Results show that as DBH increases, the average biomass of trees also increases (Figure 4). This trend proves that larger trees generally have more woody material, foliage, and structural components which contribute to a greater total biomass.

According to Vargas-Larreta et al. [41] the accurate estimation of forest biomass is required for greenhouse gas inventories, terrestrial carbon accounting and climate change modeling studies. Forests are important components in the global carbon budget since they play a key role in the global carbon cycle. Ecologists and forestry professionals have created indirect techniques for calculating biomass density especially AGB [29].

Figure 4: Distribution of Biomass in kg per DBH Class



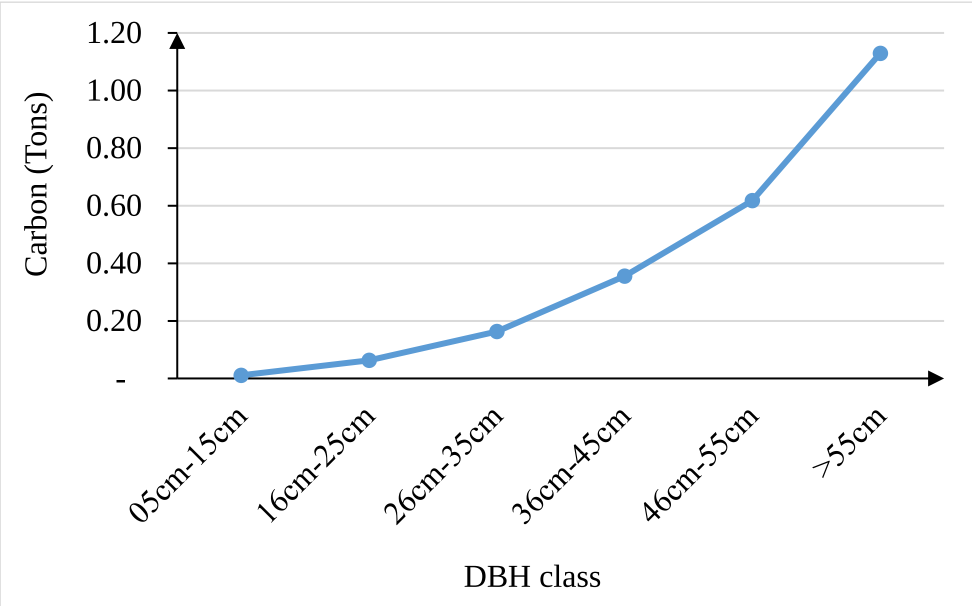
The smallest DBH class, ranging from 05 – 15 cm, exhibits the lowest average biomass. Trees in this class were typically young, contributing minimally to the forest total biomass. Low biomass value reflects the limited wood volume and structural development in smaller trees. Despite their lower individual biomass, these trees are essential for forest regeneration and long-term sustainability as they represent the future potential for biomass accumulation as they grow [27]. The biomass increase becomes more significant as trees transition from young to medium size. This trend highlights the importance of allowing young trees to grow and reach large sizes, as their biomass and carbon sequestration potential increase substantially with growth [21]. Sustainable forestry practices should focus on conserving mature trees and ensuring the continuous growth of younger trees to maintain and enhance forest ecology and biomass [27].

The most substantial increases in biomass were observed in the large DBH classes of 36 – 45 cm, 46 – 55 cm especially >55 cm. These classes show a steep rise in average biomass, with the largest trees contributing the most to the forest total biomass. The exponential nature of this increase underscores the critical role of large trees in biomass accumulation. These results align with Requena Suarez et al. [31] who noted that large trees, despite being fewer in number, have extensive wood volume and structural complexity, making them key contributors to the total forest biomass.

3.3 Above-Ground Carbon (AGC)

The average biomass per plot was 10,457.44 kg contributing to 69.568 tons of AGC per ha (Appendix 2). The greater proportion of AGC was contained in larger trees, with the relative proportion contained in different size classes (Figure 5). The AGC was obtained from biomass measurement which includes the total weight of all organic material above the ground such as trunks, branches, and leaves. The biomass values per ha signify a substantial amount of organic material which is essential for the ecosystem health and carbon storage [21].

Figure 5: Distribution of AGC in Tons per DBH Class



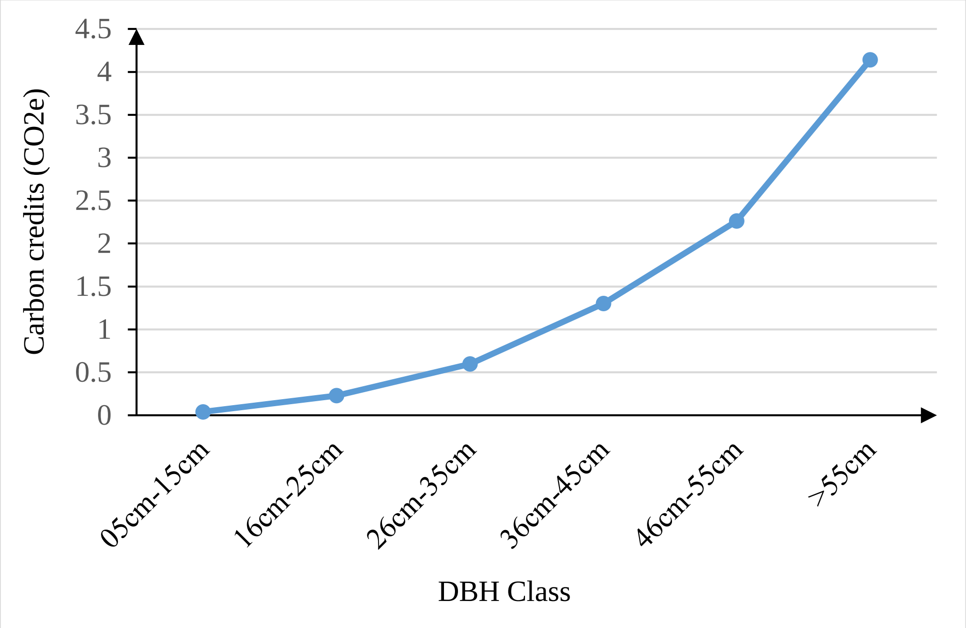
As the DBH class increases, AGC also increases, showing a positive correlation between tree size and carbon storage. This relationship was expected because larger trees have more biomass which translates to higher carbon storage capacity [36]. In the smallest DBH class 05 – 15 cm, the carbon storage is minimal, just above zero. This indicates that younger trees contribute very little to the overall carbon storage of the forest. This finding is similar to that of Sist et al. [35] who noted that tree mass growth and thus carbon accumulation decrease, remain constant, or increase as trees increase in size and age. Also, the results show that small diameter trees stored less AGC compared to large trees, hold significant promise for future carbon credit business due to their potential for growth and carbon sequestration over time. These results align with Manyanda et al. [21] who assert that as small diameter trees mature, their biomass and carbon storage capacity increases significantly. Therefore, Sawago forest reserve has a future

AGC promising for carbon storage. As the DBH classes increased from 16 – 25 cm to 26 – 35 cm, there was a noticeable rise in carbon storage. This increase reflects the growing biomass of medium size trees, which begin to play a more significant role in the forest carbon dynamics. Trees in these DBH classes were likely in their mid-growth stages, accumulating more wood and foliage, thereby increasing their ability to store carbon. Stephenson et al. [36] and Sist et al. [35] the transition from small to large trees, contributing incrementally to the forest carbon pool. Furthermore, the most substantial increases in carbon storage were observed in large DBH classes of 36 – 45 cm and 46 – 55 cm. This finding is similar to Manyanda et al. [21] who assert that the carbon storage rises steeply, indicating that trees in these size ranges have significantly more biomass. Similarly, to Lutz et al. [19] who noted that large trees contribute extremely to the forest total carbon storage, underscoring their ecological importance. Their ability to store large amounts of carbon makes them critical components of the forest carbon sequestration strategy [35]. In the largest DBH class >55 cm, the carbon storage reaches its peak, with approximately 1.2 tons of AGC. This emphasizes the critical role that very large trees play in carbon sequestration. Despite being fewer in number, these trees have extensive wood volume and structural complexity, making them key players in the forest carbon storage capacity [28]. Protecting these large trees is essential for maintaining high levels of carbon sequestration, highlighting the need for conservation efforts focused on preserving mature, and large-diameter trees [23]. According to Kayombo et al. [12] the increase in carbon storage with DBH underscores the importance of conserving and fostering the growth of large trees within the forest ecosystem. This has taken on added significance due to the rise in carbon sequestration initiatives such as carbon credit marketing.

3.4 Carbon credits generation

The findings show tree density supports substantial carbon credits accumulation, with each hectare holding an average of 255.08 CO_2e per ha which translates to a total of 208,658.46 CO_2e for the entire forest area (Appendix 2). The results show that larger diameter trees contribute disproportionately to carbon credits. Trees with DBH greater than 55 cm are especially valuable, storing the highest amount of carbon and thus generating the most carbon credits (Figure 6). This result is similar to Mganga et al. [23] who highlighted that increase in carbon credits with increasing DBH underscores the importance of large trees in carbon sequestration efforts. The significant amount of carbon credits generated by the Sawago forest reserve highlights its potential for participation in carbon trading schemes. This peak the forest capacity to attract investors interested in carbon trading and insuring long term business of carbon credits. According to van Kooten et al. [40], through maintaining and enhancing the forest health and carbon sequestration capabilities, forest managers can leverage these credits in the carbon market. By selling carbon credits can attract investors who are looking to offset their carbon emissions, providing financial incentives for forest conservation and sustainable management practices [26]. This aligns with van Kooten and Johnston [39] that carbon marketing not only supports climate change mitigation efforts but also offers economic benefits through the sale of carbon credits.

Figure 6: Distribution Between Carbon Credits per DBH Class



Furthermore, the results show that there were high regeneration rates among small trees which mean that there is a continuous supply of individuals that will grow into larger, carbon-storing trees. This result is supported by Kayombo et al. [12] that small diameter trees often represent the younger generation of the forest, ensuring the continuity and sustainability of the forest ecosystem. For example, trees within the 05 – 15 cm DBH class generate minimal carbon credits, indicating their lower biomass and carbon storage capacity. As DBH class increases to 16 – 25 cm, there was a noticeable increase in carbon credits. This trend continues more steeply in higher DBH classes. Also trees in 46 – 55 cm DBH class contribute significantly more carbon credits and those with a DBH greater than 55 cm generate the highest amount of carbon credits, reaching up to 4.0 CO_2e (Figure 6). The steep upward curve for larger DBH class >55 cm indicates that mature trees have a substantial impact on carbon storage and credit generation. This is critical for attracting investors because it shows that the forest has a high potential for increasing carbon credits over time as trees grow and mature [26]. According to Kihulla [13] investors looking to engage in carbon trading are interested in long-term and sustainable sources of carbon credits and the graph clearly illustrates that the Sawago FR can provide such opportunities. Furthermore, carbon credit programs typically reward ongoing and future carbon sequestration [26]. The results show that in Sawago FR there was high number of small diameter trees which can be viewed as a long-term investment in carbon storage. This is because as these trees grow and accumulate more biomass, the forest overall carbon sequestration capacity increases, enhancing its value in carbon credit markets. Investors would be particularly interested in the long-term benefits that the forest offers [24]. As smaller diameter trees grow into larger classes, the amount of carbon credits they generate will increase providing a continuous and growing return on investment [13]. The results suggest that the forest ability to sequester more carbon as young trees mature, the investment in forest conservation and sustainable management can yield increasing carbon credits over time.

4. Conclusion

The AGB was 148,017.6 kg per ha, amounting to a total biomass of 121,078,412.46 kg for the entire 818 ha forest area indicating a substantial amount of biomass which is crucial for the forest role in carbon sequestration and ecological health. The results highlighted that a significant portion of the forest biomass is stored in the smaller DBH classes, emphasizing the importance of young tree recruitment and growth in carbon sequestration efforts. The successful quantification of AGB and the subsequent determination of carbon storage and potential carbon credits underscore the Sawago Forest Reserve significant role in carbon sequestration and climate change mitigation.

The carbon storage potential was further translated into carbon credits, which represent a critical component of the forest contribution to climate change mitigation. The estimated ABG carbon stocks were used to compute the equivalent amount of CO_2 captured by the forest.

The data obtained from this study not only highlight the forest ecological value but also its economic potential through carbon trading schemes. These findings provide a solid foundation for integrating the forest into carbon offset programs, which can offer financial incentives for local communities and support sustainable forest management practices. This contributes not only to the conservation of the forest but also to the economic development of the surrounding communities through sustainable practices. The methodology and findings of this study can serve as a model for similar assessments in other forested regions in Tanzania, thereby enhancing the country's overall efforts in combating climate change.

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