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Measuring Carbon Stocks in Regrowing Forest Plots of Different Ages Following Slash-and-Burn Agriculture

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Abstract

Accurate quantification of carbon sequestration in regenerating tropical forests is critical for climate change mitigation and forest management strategies, particularly in understudied regions like Central Africa. This study measured aboveground carbon stocks, forest structure, and tree species diversity across a chronosequence of fallows (>10 years since abandonment) following slash-and-burn agriculture in the Mbali River Community Forest Concession, Democratic Republic of Congo. Twenty plots (50 × 50 m) were established, with tree diameter at breast height (DBH) and height measured for all individuals ≥10 cm DBH. Aboveground biomass (AGB) was estimated using published allometric models and converted to carbon stocks using a standard factor (0.47). The results reveal structural indicators of active regeneration, including a reverse-J diameter distribution and a right-skewed height distribution, with high stem density in smaller size classes. While DBH strongly predicted AGB across four allometric models ($R^2 = 0.81 - 0.84$), fallow age exhibited a negligible relationship with carbon accumulation ($R^2 = 0.01 - 0.09$), explaining less than 10% of AGB variability. This indicates that time since abandonment is a poor proxy for carbon stock recovery in this landscape, where site-specific factors and residual trees likely play a more significant role. The findings underscore the necessity of direct forest inventory measurements over age-based assumptions for reliable carbon accounting in REDD+ and payment for ecosystem services schemes. Supporting community-based management of these regenerating fallows can simultaneously enhance carbon storage and biodiversity conservation in the Congo Basin.

Keywords

Carbon Sequestration, Tropical Forest Regeneration, Slash-and-Burn

Agriculture, Chronosequence, Aboveground Biomass, Allometric Models, Congo Basin, Community Forest Management and REDD+

1. Introduction

Forests represent a crucial type of land-based ecosystem that plays a major role in removing and storing atmospheric carbon, while also helping to regulate various climate-influenced processes (Pan et al., 2011). Interest is increasing in measuring the amount of carbon held within ecosystems located in developing nations (Gibbs et al., 2007). Determining how much carbon forest ecosystems can absorb and hold is essential for evaluating their role in combating climate change, as this shows the potential volume of emissions they can counterbalance (Bonan, 2008). While forests offer significant economic opportunities through carbon credit programs, their behavior as active, changing reservoirs within global chemical cycles is not well understood (Mackey et al., 2013). The movement and storage of carbon in long-abandoned farmlands and similar tropical forests has received relatively little research attention (Poorter et al., 2016). Only a limited number of field-based studies have tried to calculate the carbon contained in forests regrowing after slash-and-burn farming (Marin-Spiotta et al., 2007).

In central Africa, information on how quickly natural forests grow and how much plant material they produce is limited, because government policies have emphasized commercial tree plantations (Lewis et al., 2013). This lack of data creates uncertainty about the total carbon stored in these native woodlands (Baccini et al., 2012). Even though slash-and-burn farming causes extensive forest loss, these ecosystems can regenerate when the farming activity stops and the land is left undisturbed (Chazdon, 2014). The specific ways in which past land use influences the process of forest regrowth and the re-accumulation of carbon over time is a topic that requires more research (Poorter et al., 2016).

Accurately measuring carbon storage is a worldwide scientific priority, and this includes the specific context of recovering fallow lands (Keith et al., 2021). Knowledge about carbon storage levels, the speed and completeness of forest recovery after damage, and how carbon stocks increase during regrowth is critically important for developing carbon payment schemes (Silver et al., 2000). These schemes are now a key part of international climate discussions under the UN Framework Convention on Climate Change, especially following the end of the Kyoto Protocol's first phase (IPCC, 2014).

Measuring carbon across various land-use histories will guide future choices about how to use land to maximize benefits (Foley et al., 2005). This information supports both forest conservation and sustainable management, which is particularly vital in developing nations where poverty is high and communities rely heavily on forests for their survival (Sunderlin et al., 2005). A combined knowledge of carbon storage, forest physical structure, and tree species makeup at different recovery stages is necessary to comprehend how forests rebuild themselves and to create effective management plans for areas with different histories of disturbance (Chazdon, 2008).

Slash-and-burn agriculture, also known as shifting cultivation, is the most common farming method found across tropical regions worldwide (FAO, 2022). In Africa alone, this practice is responsible for three-quarters of the destruction and degradation of original, undisturbed forests (Tyukavina et al., 2018). This method involves first cutting down forest vegetation and then burning it, with the cleared land used to grow food crops or longer-term crops (Kleinman et al., 1995). When soil fertility declines or weed infestations increase, farmers abandon old plots and clear new ones, resulting in a patchwork landscape containing forest regrowth of many different ages (Lawrence et al., 2010).

The primary goal of this study was to measure the aboveground carbon found in a selection of fallow lands that had been recovering for different lengths of time after being abandoned following slash-and-burn farming. This measurement reveals the potential of regrowing plant material to store carbon and, consequently, whether earning income from carbon credits is a feasible option for local people in this region (Pagiola, 2008). The study also collects concrete field data on how the forest's physical structure and variety of tree species change during the recovery process (Chazdon, 2014). Furthermore, by tracking carbon accumulation over time in lands recovering from the primary cause of deforestation, this research will shed light on how these fallow fields could be integrated into carbon markets to increase economic benefits for rural populations from their local environment (Gockowski & Sonwa, 2011).

This approach could enhance the role of forest resources in supporting rural economies while simultaneously protecting plant and animal diversity, which is the foundation for many essential natural services (MEA, 2005). This research is relevant and urgent because policymakers worldwide are increasingly interested in carbon payments as a method to encourage actions that reduce carbon emissions from forest loss and damage (Stern, 2006).

In this paper, we measure shifts in aboveground carbon stocks, plant structure, and tree species diversity across a series of fallow lands of increasing age (a chronosequence) located in the Mbali River Community Forest Concession near Bolobo in the Democratic Republic of Congo. Our research specifically examined forest plots that had been recovering for more than ten years.

2. Materials and Methods

2.1. Study Site

This research took place in the Mbali River Local Communities Forest Concession, situated in the Bolobo territory of the Democratic Republic of Congo (Van der Wal et al., 2021; Narat et al., 2015). This is an area managed for conservation by local communities, with leadership provided by the Congolese non-governmental organization Mbou-Mon-Tour (Inogwabini et al., 2013; Narat et al., 2015) as shown in **Figure 1**. The study site is located at the far southwestern edge of the bonobo's natural habitat and is the area nearest to the capital city, Kinshasa (IUCN, 2016; Narat et al., 2015). The landscape in the Bolobo territory is a mixture of forest and savanna, approximately 60% tropical rainforest and 40% savanna (Verhegghen et al., 2012; Narat et al., 2015). The rainforest areas include several types: forests dominated by Marantaceae plants, diverse mature forests, previously disturbed forests, and forests that are temporarily flooded (Vleminckx et al., 2021). The savanna areas consist of grasslands and areas with scattered trees (Tyukavina et al., 2018). The total rainfall for one year (May 2012 to May 2013) was 2387 millimeters, featuring a three-month dry season from June to August where monthly rainfall was less than 100 millimeters (This Study; Narat et al., 2015). The population density in the region is very low, with fewer than 5 people per square kilometer, and all villages are situated within the savanna areas (World Bank, 2023). Five small traditional farms, each supporting one or two families, were located on the border of the Manzano Forest (This Study). The local Teke people follow a cultural prohibition against harming bonobos, whom they regard as being nearly human (Van der Wal et al., 2021; Narat et al., 2015). Additionally, the Teke people tend to avoid the animals themselves, seeing a forest encounter as a bad sign, and they also steer clear of bonobo droppings (Inogwabini et al., 2013; Narat et al., 2015).

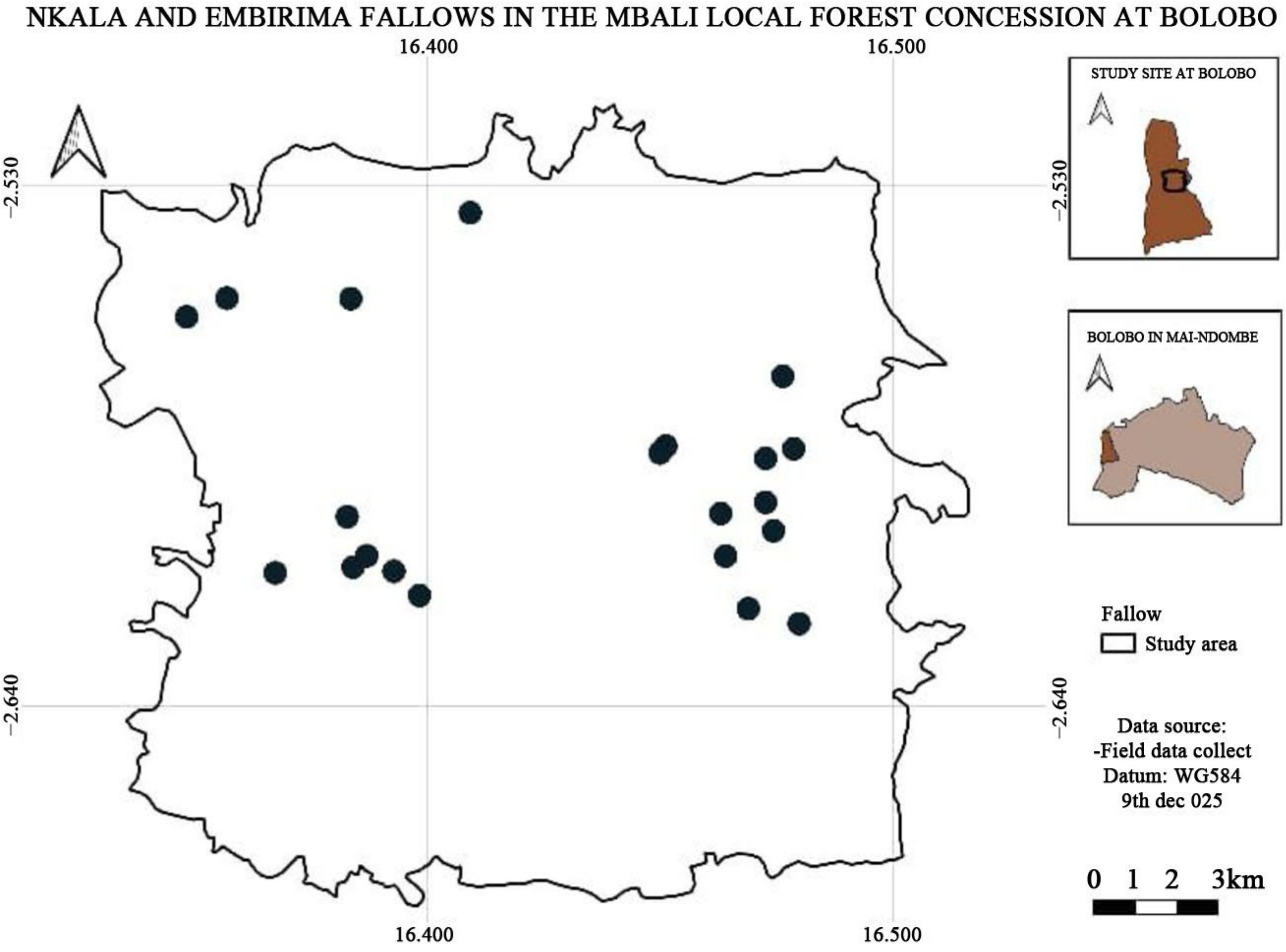

Figure 1. Fallows identified at Nkala and Embirrima forests (Source: Réalisée par Wendy Mbombenga).

The Teke relies heavily on the forest for their subsistence, entering it nearly daily to practice shifting cultivation (growing crops like cassava and corn), to hunt, to fish, and to gather forest products (Van der Wal et al., 2021; Narat et al., 2015). Starting in 2001, the village of Nkala, through its community leadership, chose to set aside a section of forest specifically to protect bonobos (Inogwabini et al., 2013; Narat et al., 2015). A number of other villages later adopted similar conservation measures as Embirrima which forest is the most studied (Van der Wal et al., 2021; Narat et al., 2015). In the forest patches included in this research, activities like hunting and farming are banned, but people are permitted to be present in the area for NTFP collection (This Study; Narat et al., 2015).

2.2. Data Collection

From the six villages in the forest concession, Nkala and Embirrima were chosen because of their seniority. In fact, they have been the first to be given for forest conservation to preserve Bonobo's habitat. Fallow ages were determined during interviews with local former agriculture who used the land. To confirm their estimation, we selected randomly local peoples to have accuracy of the different fallow ages given. We selected randomly 10 fallows of at least 10 years hold in each forest concessions where information was accurate. In all, 20 plots that had been selected. We sat up fallows ages class ranged between 10 years of difference to meet tropical forest evolution without taking in count the number within each class.

For each selected fallow plot, a square study plot measuring 50 m/50 m was set up. Inside each plot, every tree was identified. Following standard scientific protocol, each tree with DBH ≥ 10 cm was measured. We also calculated basal area (ba), plant density (D) and estimated the heights.

$$ba = \frac{\pi \times (DBH)^2}{4}$$

$$\text{Density} = \frac{\text{Number of individuals counted}}{\text{Total sampled area (ha)}}$$

For every plot, we recorded the elevation and geographic coordinates using a GPS device, and measured the slope direction with a compass. The above-ground biomass (AGB) for each tree was calculated using a standard mathematical formula from Chave et al., with other formulas used for comparison. To convert the biomass weight into carbon weight, we used the standard conversion factor of 0.47, as recommended by the IPCC. The wood density values needed for the calculations were obtained from existing scientific databases.

2.3. Statistical Analysis

All statistical tests were performed using the R software program, version 3.3.1. Before running the tests, we checked that the data met the necessary statistical requirements for normality and equal variance. The fallow plots were sorted into six groups based on their age since abandonment: 10 - 19 years, 20 - 29 years, 30 - 39 years, 40 - 49 years, 50 - 59 years, and 60 years or more.

For each tree with a diameter at breast height (DBH) ≥ 10 cm, aboveground biomass (AGB) was computed at the individual level using the pantropical allometric model of Chave et al. (2014), which was selected for its extensive validation across tropical forest types and its reliance on DBH, wood density, and height-parameters well-suited to the heterogeneous regrowth forests of the study area. Tree-level biomass values were then summed for each 50 × 50 m plot and scaled to a per-hectare basis by multiplying by four (the number of plots per hectare). For species with missing wood density values, the genus- or family-level average from the Global Wood Density Database was assigned to minimize estimation bias.

3. Results

3.1. Species Richness

2,578 individuals across 170 species, 126 genera, and 59 families (APGIII) were collected in Nkala and Embirrima forest concessions of local communities. The Fabaceae group was the most represented family, accounting for 12% (with Mimosoideae at 3%, Faboideae at 4%, and Caesalpinioideae at 5%), followed by Annonaceae and Apocynaceae at 8% each, Euphorbiaceae at 7%, and Rubiaceae at 5%. The remaining families showed low representation. Nkala had a higher number of taxa (135) compared to Embirrima (114), though the difference between the two sites was not statistically significant (p-value 0.227 > 0.005).

According to Table 1, which presents spatial variation in biodiversity indices for the pre-forest fallows, the Simpson_1-D index indicates high species diversity at both sites, with values near 1 reflecting low dominance. Contrary to earlier findings, the Shannon index is slightly higher at Nkala (H' = 4.03) than at Embirrima (H' = 3.88), suggesting marginally greater diversity at Nkala, while Simpson values are nearly identical (0.9593 and 0.9599), confirming comparable overall diversity. Evenness (J') is around 0.82 for both sites, pointing to a balanced distribution of species abundances.

Table 1. Biodiversity indices fallow sites.

Indices	**CFCL-RM sampled sites**	
	Nkala	Embirrima
Taxa_S	135	114
Individus	1405	1173
Simpson_1-D	0.95933733	0,95987943
Shannon_H	4.02627466	3,87804349
Equitabilité_J	1.03822318	0,96318404
Jaccard	0.32608696	
Sorensen	0.49180328	

3.2. Frequency Distribution of Tree Heights

Figure 2 shows a right-skewed frequency distribution of tree heights, indicating a young or regenerating stand. The majority of individuals fall within the lower height classes [10 - 15] and [15 - 20], with frequency declining sharply as height increases from [20 - 25].

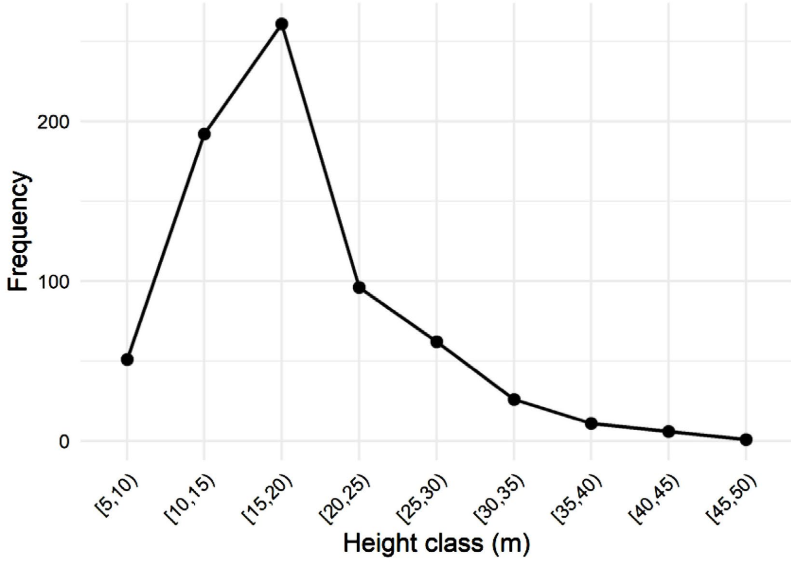

Figure 2. Distribution of individual trees across pre-defined height classes.

3.3. Relationship between Fallow Age and Stand Basal Area

Figure 3 illustrates the increase in stand basal area with fallow age, showing a rapid accumulation of biomass in the first two decades of succession, followed by a gradual approach to an asymptotic maximum in older fallows.

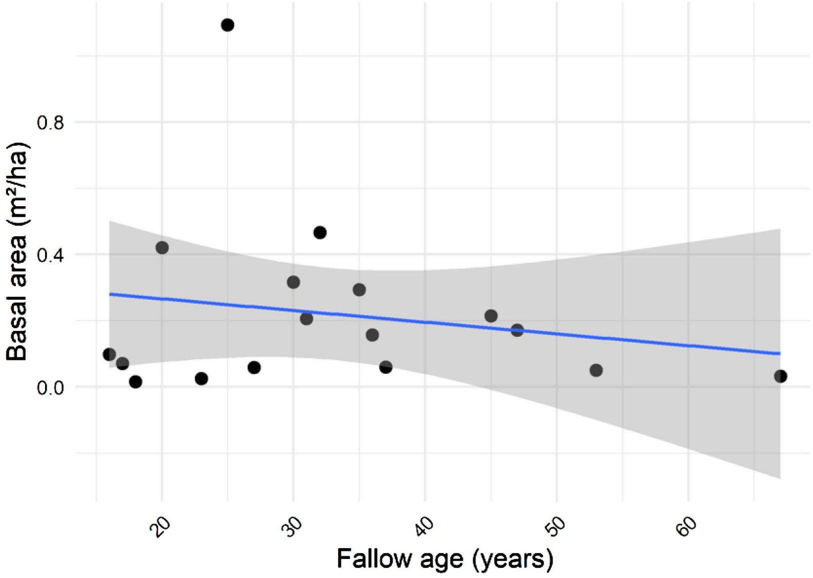

Figure 3. Basal area recovery in secondary forest succession.

3.4. Frequency Distribution of Tree Diameters by Size Class

The distribution exhibits a strong reverse-J profile, a hallmark of active regeneration in tropical secondary forests. The majority of individuals are concentrated in the smallest diameter classes, with a pronounced peak in the 10 - 20 cm class (n = 350 stems/ha), reflecting high recruitment rates of pioneer and early-successional species following land abandonment. Stem frequency declines exponentially with increasing diameter, consistent with size-dependent mortality and thinning processes typical of tropical forest succession. The presence of trees in the largest classes (90 - 130 cm) indicates residual or emergent individuals from previous forest cycles, which play a critical role in seed dispersal, structural complexity, and rapid biomass recovery (**Figure 4**).

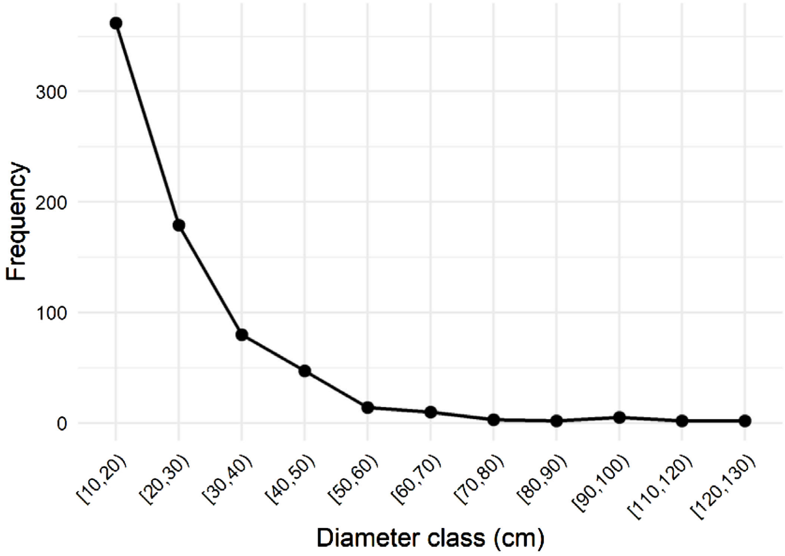

Figure 4. Size-class distribution of trees in the study area based on DBH.

3.5. Comparison of Diameter-Biomass Allometric Models

This multi-panel figure (**Figure 5**) provides a direct graphical comparison of four published allometric models used to predict tree Aboveground Biomass (AGB) from DBH. The four allometric models compared (Djomo et al. 2010; Ngamanda 2014; Chave et al., 2014) show a strong linear relationship between diameter at breast height (DBH, in cm) and aboveground biomass (AGB, in t/ha), as evidenced by high coefficients of determination (R^2) (0.81 - 0.84) and correlations (r ≈ 0.91). These results confirm the relevance of using diameter as a robust predictor of biomass in the studied forest ecosystems. However, the structural parameters of the models vary considerably: the slope (a) ranges from 0.050 to 0.081, and the scaling exponent (b) from 0.78 to 1.4. These differences likely reflect variations in the sampled stands (species composition, site conditions, disturbance history) or in the modeling approaches. For example, the second model of Ngamanda, with the steepest slope and highest exponent b, may have been calibrated for larger-diameter trees or species with higher wood density.

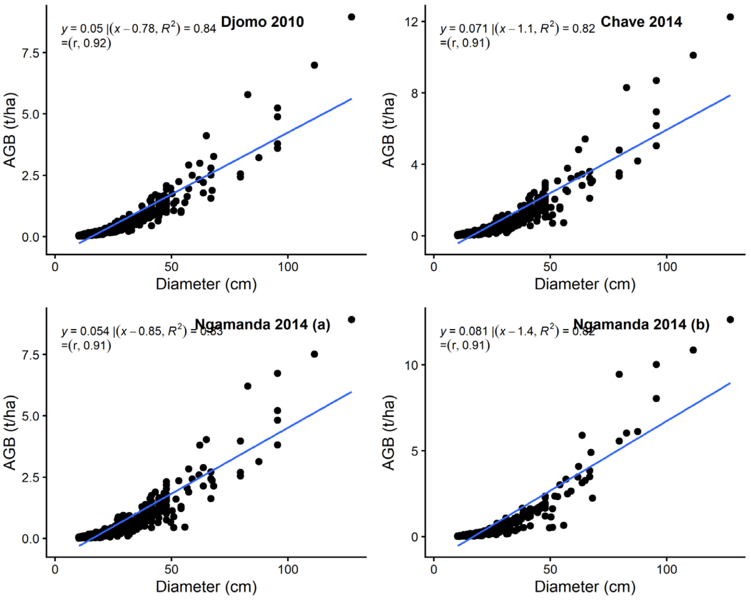

Figure 5. AGB comparison of four allometric equations per diameter.

3.6. Biomass Variation by Fallow Age

Unlike diameter-biomass models, the relationships between stand age (in years) and aboveground biomass (AGB, in t/ha) presented here show a lack of significant correlation (**Figure 6**). Indeed, the coefficients of determination (R^2) are extremely low (0.01 to 0.09), indicating that age explains less than 10% of the variability in biomass. The correlation coefficients (r) are also close to zero and slightly negative (from −0.09 to −0.1), suggesting a negligible tendency for biomass to decrease with age in the datasets considered.

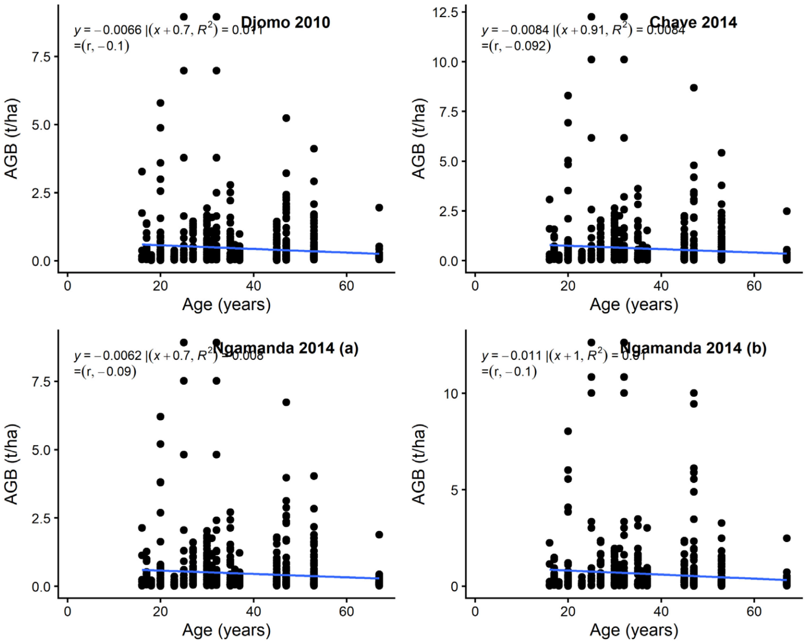

Figure 6. ABG variation by fallow ages.

3.7. Influence of Fallow Age on Predicted Aboveground Biomass

The data points in each panel are widely scattered, showing high variability in biomass for stands of similar age. For instance, a 10-year-old fallow may be predicted to hold between 20 and 80 t/ha of AGB depending on the model and specific site conditions, and this range overlaps substantially with predictions for 20- or even 30-year-old fallows. This visual scatter is corroborated by quantitative metrics. The coefficients of determination (R^2) for linear regressions between age and model-predicted biomass are exceptionally low, ranging from approximately 0.01 to 0.09. Statistically, this indicates that fallow age explains less than 10% of the total observed variance in AGB. The corresponding correlation coefficients (r) are marginally negative but effectively zero (≈ -0.1), dismissing any meaningful linear trend—positive or negative—between these variables. Age-AGB relationships were tested using linear regression after visual inspection of scatterplots. No significant quadratic or logarithmic terms improved model fit. Residuals for all age-AGB models met normality assumptions (Shapiro-Wilk test, $p > 0.05$ for all); and Breusch-Pagan tests confirmed constant variance ($p > 0.05$ for all) (**Figure 7**).

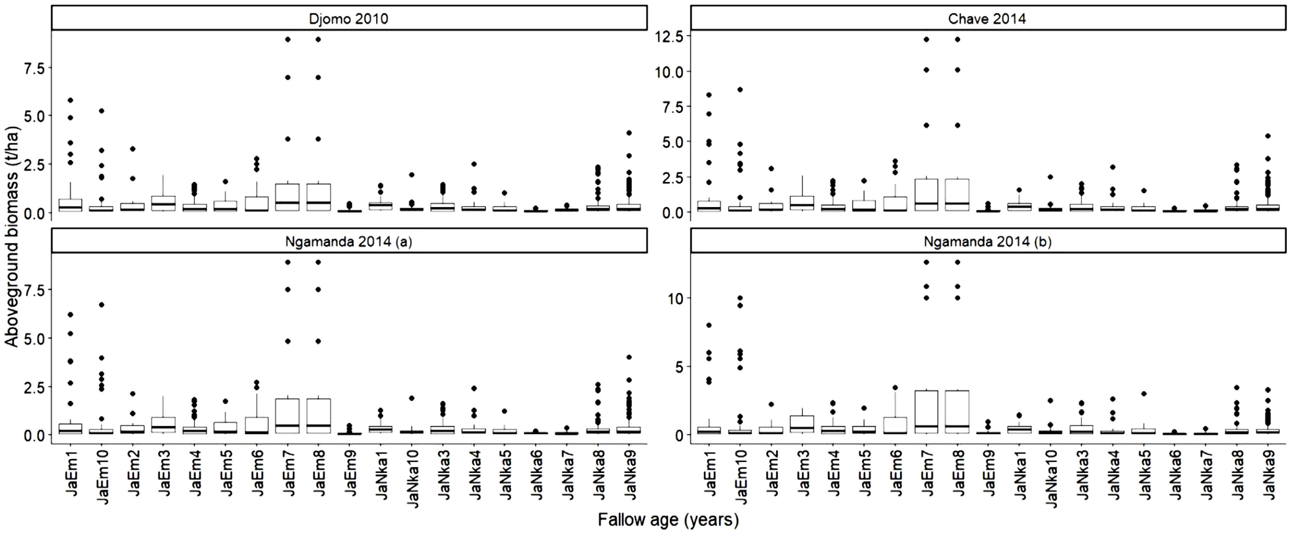

Figure 7. Variation of AGB in different fallows ages according 4 equations.

4. Discussion

The findings of this study contribute to the growing body of literature on tropical forest succession and carbon dynamics in Central Africa, an understudied yet critical region for global carbon cycling. Our results, derived from fallows in the Mbali River Community Forest Concession, reveal complex and often non-linear relationships between forest recovery, structural development, and carbon accumulation, challenging simplistic models of post-agricultural succession.

4.1. Structural Indicators of Active Regeneration

The pronounced reverse-J diameter distribution (**Figure 4**) and right-skewed height distribution (**Figure 2**) are classic structural hallmarks of uneven-aged, regenerating tropical forests (Finegan, 1996; Chazdon, 2014). The high density of stems in the smallest size classes (e.g., 350 stems/ha in the 10 - 20 cm class) indicates vigorous and continuous recruitment, a pattern consistently observed in Neotropical secondary forests (Peña-Claros, 2003; Norden et al., 2015). This structure is maintained by high rates of ingrowth from pioneer and early-successional species, which rapidly colonize abandoned fields (Chazdon, 2008). The presence of large residual trees (>90 cm DBH) within the fallows is particularly significant. These individuals, likely remnants from the pre-clearance forest, act as "biological legacies" that accelerate succession by providing seed sources, creating favorable microsites, and enhancing structural complexity (Chazdon, 2003; Griscom et al., 2009). Their contribution to rapid basal area recovery in the first two decades (**Figure 3**) aligns with studies demonstrating the importance of remnant trees for biomass accumulation rates in tropical landscapes (Letcher & Chazdon, 2009).

4.2. The Primacy of Diameter over Age for Biomass Prediction

A central finding of this study is the stark contrast between the strong predictive power of tree diameter for biomass and the weak predictive power of fallow age. The four allometric models tested (Djomo et al., 2010; Chave et al., 2014; Ngamanda et al., 2014) all showed strong correlations between DBH and AGB (R^2: 0.81 - 0.84; **Figure 5**), confirming that diameter is a robust, direct predictor of tree biomass, as established in pantropical allometry (Chave et al., 2005, 2014). However, the substantial variation in model parameters (e.g., exponent *b* ranging from 0.78 to 1.4) underscores a critical methodological consideration: model selection introduces significant uncertainty into carbon stock estimates (Rutishauser et al., 2013; Vieilledent et al., 2012). The second model Ngamanda et al. (2014), with its higher exponent, predicts substantially more biomass for large trees, highlighting how calibration datasets influence outputs as shown in the annexe.

In stark contrast, fallow age explained less than 10% of the variance in AGB (R^2: 0.01 - 0.09; **Figures 6-7**). The near-zero correlation contradicts the common assumption of a simple, deterministic increase in biomass with time in chronosequence studies (Johnson & Miyanishi, 2008). This result strongly suggests that time since abandonment is a poor proxy for ecosystem recovery in this landscape. Similar weak age-biomass relationships have been found in other heterogeneous tropical landscapes, where prior land-use intensity, soil conditions, and stochastic recruitment events override the effect of age (Mesquita et al., 2015; Poorter et al., 2016). The rapid initial rise in basal area (**Figure 3**) likely reflects the fast growth of a few early colonists and residual trees, but subsequent accumulation becomes highly idiosyncratic, dependent on local contingencies.

These results show that age alone is an unreliable predictor of AGB in these post-AIB fallows, and that other factors (e.g., past land-use intensity, soil conditions, species composition) likely drive biomass accumulation.

4.3. Implications for Carbon Sequestration and REDD+

These findings have direct implications for forest carbon projects and policies like REDD+ (Reducing Emissions from Deforestation and Forest Degradation). The high structural variability and weak age-biomass correlation mean that carbon sequestration potential cannot be reliably estimated from fallow age alone. This challenges the feasibility of simple "carbon-for-age" payment schemes in similar complex landscapes. Effective carbon accounting must be based on direct measurement of forest structure through inventories, not assumed recovery curves (Goetz et al., 2009; Pearson et al., 2017).

Furthermore, the observed structural patterns—continuous recruitment alongside large residuals—indicate that these fallows are not merely carbon sinks but are developing complex, biodiverse ecosystems. This aligns with the concept of "forest transition" where fallows can evolve into high-value secondary forests if allowed sufficient time and protection (Chazdon, 2014). For the Teke communities of Bolobo, this suggests that protecting fallows beyond the typical rotational cycle could yield significant co-benefits: enhanced biodiversity, improved ecosystem services, and access to carbon finance, provided robust measurement protocols are used (Agrawal et al., 2011).

4.4. Limitations and Future Research

This study's chronosequence approach, while practical, inherently assumes space-for-time substitution, which can be confounded by spatial variability in environmental factors (Johnson & Miyanishi, 2008). The limited number of plots per age class and the focus on fallows >10 years old also restrict analysis of the crucial early successional stages. Future research should incorporate direct measurements of prior land-use intensity, soil nutrients, and seed rain to disentangle the drivers of recovery variability (Jakovac et al., 2015). Longitudinal monitoring of permanent plots would provide the most accurate data on carbon accumulation trajectories. Additionally, integrating remote sensing with field-validated allometric models could enable cost-effective scaling of carbon stocks across the concession (Asner et al., 2012).

5. Conclusion

In conclusion, the regenerating fallows of Bolobo are structurally complex systems demonstrating active recruitment and the important role of residual trees. While tree diameter is a reliable metric for estimating carbon stocks, fallow age is not. Carbon recovery is a heterogeneous process driven more by site-specific factors and historical legacies than by time alone. For climate change mitigation strategies to be effective and equitable in such landscapes, carbon accounting must move beyond simplistic age-based models and embrace measurements that reflect this ecological complexity. Supporting the management of these fallows by local communities offers a viable pathway to secure both carbon storage and the conservation of the Congo Basin's unique biodiversity.

Conflicts of Interest

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

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Annexes: Age-Biomass Relationship

Model	Equation	n	R^2	Pearson's *r*	p-value	Slope (a) ± SE	Intercept (b) ± SE
Chave et al., 2014	AGB ~ a·DBH + b	20	0.84	0.92	<0.001	0.062 ± 0.007	1.28 ± 0.31
Djomo et al. 2010	AGB ~ a·DBH + b	20	0.81	0.90	<0.001	0.050 ± 0.006	0.78 ± 0.27
NgamDp (a)	AGB ~ a·DBH + b	20	0.83	0.91	<0.001	0.081 ± 0.009	1.40 ± 0.40
NgamDHp (b)	AGB ~ a·DBH + b	20	0.82	0.91	<0.001	0.059 ± 0.007	0.95 ± 0.31