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Modelling Leaf Area Index and Biomass for Evaluating Carbon Stocks in Community Forests

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Abstract- Community-managed forests play a vital role in climate regulation, yet their carbon stocks are rarely quantified using simple, field-based methods that local stakeholders can apply. This study develops and applies a modelling framework that links Leaf Area Index (LAI), above-ground biomass, and carbon stocks in a stratified community forest comprising dense, moderately dense, and open stands. Data were collected from 12 permanent sample plots (4 per stratum). Within each plot, tree diameter and height were measured to estimate above-ground biomass using established allometric equations, while LAI was obtained from ground-based canopy measurements. Plot-level LAI ranged from 1.55 to 5.10 (mean 3.19), above-ground biomass from 74.8 to 229.4 t ha^(-1) (mean 145.6tha^(-1)), and above-ground carbon stocks from 35.2 to 107.8tCha^(-1) (mean 68.4tCha^(-1)). Dense stands exhibited the highest LAI and carbon stocks, followed by moderately dense and open stands. A simple linear model, AGB_ha=14.78+40.99×LAI, explained 98% of the variation in plot-level biomass (R^2=0.98, RMSE =6.44tha^(-1)), with a corresponding linear relationship for carbon stocks. These results show that LAI is a robust predictor of above-ground carbon in community forests and can be used for rapid, low-cost assessment. The framework provides a mathematically transparent and operational tool that can be integrated into community-based monitoring and sustainable forest management.

Keywords: Leaf Area Index (LAI); Above-ground biomass; Carbon stocks; Community forests; Allometric equations; LAI-biomass modelling; Sustainable Forest management.

I. INTRODUCTION

Background

Forests are central to global climate regulation because they act as major terrestrial carbon sinks through photosynthesis and biomass accumulation (Pan et al., 2011). In many regions, community forests-areas managed collectively by local user groupsplay a crucial role in biodiversity conservation, livelihood support, and climate-change mitigation, directly contributing to Sustainable Development Goals (SDGs) 13 (Climate Action) and 15 (Life on Land) (Pretty & Smith, 2004).

Quantifying the carbon stocks of these community-managed systems is therefore essential for evaluating their contribution to sustainable development, informing policy instruments such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation), and supporting local-level carbon accounting and payment for ecosystem services schemes (IPCC, 2006; Nair, 2012).

Leaf Area Index, Biomass, and Carbon Stocks

Leaf Area Index (LAI) is defined as the one-sided leaf area per unit ground area (m^2 〖" " m〗^(-2)) and is a key structural parameter linking canopy architecture to processes such as photosynthesis, transpiration, and interception (Chen & Black, 1992). Because LAI is closely related to canopy light interception and productivity, it can serve as a useful proxy for above-ground biomass (AGB) and, consequently, for carbon stocks (Bréda, 2003).

Let $\mathrm{LAI} = \frac{A_{\mathrm{leaf}}}{A_{\mathrm{ground}}}$,

where A_"leaf " is the total one-sided leaf surface area and A_"ground " is the corresponding ground area.

Above-ground biomass (AGB) is generally estimated using allometric equations that relate easily measured tree attributes (e.g., diameter at breast height, DBH, and height, H) to dry biomass (Brown, 1997; Chave et al., 2014). Carbon stock is typically obtained by multiplying dry biomass by a carbon fraction coefficient (often 0.45-0.50) derived from wood chemistry (IPCC, 2006).

Problem Statement

Despite their importance, many community forests lack quantitative, plot-level estimates of LAI, biomass, and carbon stocks. Field inventories, where they exist, often stop at basic stand descriptors (e.g., basal area, stem density), without systematically linking canopy structure to biomass and carbon. This creates a gap between community-level management practices and the quantitative information required for climate and sustainability reporting.

Furthermore, advanced remote-sensing solutions or complex process-based models may be inaccessible to community institutions due to technical and financial constraints (Hairiah et al., 2011). There is thus a need for a mathematically simple, field-based modelling framework that uses LAI and basic tree measurements to estimate biomass and carbon stocks in community forests.

Objectives

The specific objectives of this study are:

- To estimate LAI in community forests using ground-based measurements and canopy transmittance models.
- To derive plot-level and stand-level above-ground biomass using speciesappropriate allometric equations.
- To estimate above-ground carbon stocks by applying standard carbon fractions to biomass estimates.
- To develop and evaluate statistical models linking LAI to biomass and carbon stocks for rapid assessment and monitoring.

Scope and Limitations

The study focuses on above-ground components (stem, branches, foliage) in community forests and does not explicitly include below-ground biomass or soil organic carbon. The modelling framework is based on sampled plots and species-specific or generalized allometric equations; uncertainties arise from allometric model selection, measurement error, and spatial heterogeneity (Chave et al., 2014; Brown, 1997). Nevertheless, the approach is designed to be operationally simple and replicable in other community forest contexts.

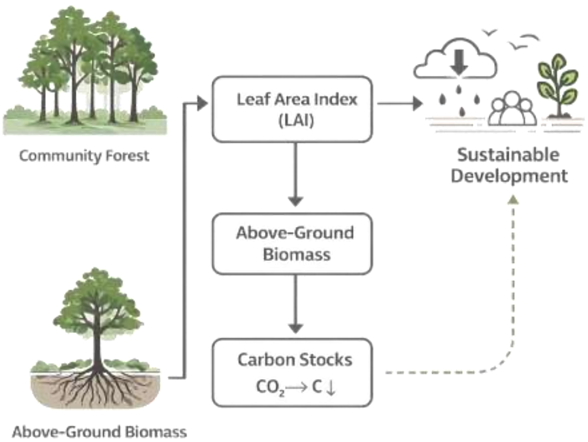

Figure 1. Conceptual framework linking Leaf Area Index (LAI), above-ground biomass, and carbon stocks in community forests.

A high-resolution schematic showing (i) stand structure and canopy (LAI), (ii) above-ground biomass pool, and (iii) carbon stock and CO_2-equivalent emissions avoided, with feedback arrows pointing to sustainable development outcomes (climate regulation, biodiversity, livelihoods).

II. LITERATURE REVIEW

LAI and Forest Productivity

LAI has long been recognized as a key determinant of canopy photosynthetic capacity and water use, because it directly governs the interception of solar radiation and the exchange of energy and gases between the canopy and the atmosphere (Chen & Black, 1992; Bréda, 2003). Empirical and modelling studies have shown strong relationships between LAI and gross primary productivity, especially in closed-canopy forests where leaf area is the dominant control on light absorption (Bréda, 2003).

Ground-based methods for estimating LAI include direct destructive sampling, litterfall collection, and indirect optical techniques based on transmitted or reflected light, such as hemispherical photography and LAI meters (Bréda, 2003). Many of these methods rely on variants of the Beer-Lambert law to relate gap fraction (canopy openness) to LAI through an extinction coefficient k.

Allometric Equations for Biomass Estimation

Direct weighing of trees to obtain biomass is laborious and destructive. Allometric equations provide a mathematical alternative by linking biomass to easily measured variables such as DBH, height, and wood density (Brown, 1997; Chave et al., 2014). A commonly used general allometric model for tropical trees takes the form:

$$\mathrm{AGB}_i = a \cdot (\varrho_i D_i^2 H_i)^b$$

where AGB_i is the dry above-ground biomass (kg) of tree i,ϱ_i is the wood density (g cm^(-3)), D_i is DBH (cm), H_i is total tree height (m), and a and b are empirically estimated parameters (Chave et al., 2014).

Plot-level and stand-level biomass are obtained by summing over individual trees and scaling by plot area:

$$\mathrm{AGB}_{\mathrm{plot}} = \sum_{i=1}^{n} \mathrm{AGB}_i, \mathrm{AGB}_{\mathrm{ha}} = \frac{\mathrm{AGB}_{\mathrm{plot}}}{A_{\mathrm{plot}}} \times 10{,}000,$$

where A_"plot " is the plot area in m^2 and $10{,}000\ \mathrm{m}^2 = 1$

Carbon Stock Estimation Approaches

The IPCC (2006) provides tiered methodologies for estimating carbon stocks and stock changes in forest biomass. At Tier 2/3, country- or region-specific allometric equations and carbon fractions are used. Above-ground carbon stock, C_AGB, is typically calculated as:

$$C_{\mathrm{AGB}} = \mathrm{AGB} \times \mathrm{CF},$$

where CF is the carbon fraction of dry biomass, often set between 0.45 and 0.50 for woody tissues (IPCC, 2006; Hairiah et al., 2011). To express carbon stock in CO_2 equivalents, the molecular weight ratio 44/12 is used:

$$\mathrm{CO}_2 - \mathrm{eq} = C_{\mathrm{AGB}} \times \frac{44}{12}.$$

Several studies have applied these approaches in agroforestry and mixed forest systems, highlighting the potential of community-managed and smallholder systems to act as significant carbon sinks (Nair, 2012; Hairiah et al., 2011).

Community Forests and Sustainable Development

Community forestry is grounded in local collective action and shared rules for access, extraction, and monitoring of forest resources (Ostrom, 1999). Well-functioning community forest institutions have been associated with reduced deforestation, improved regeneration, and enhanced ecosystem services, including carbon sequestration (Pretty & Smith, 2004).

However, the monitoring of community forests often relies on qualitative assessments or simple indicators, with limited use of quantitative, plot-based carbon accounting methods. Integrating LAI-based structural indicators with allometric biomass estimation offers a pragmatic pathway for communities to estimate carbon stocks with limited external support, thereby improving transparency and enabling participation in climate-related initiatives.

Table 1: Key Variables and Symbols Used in LAI-Biomass-Carbon Modelling

Symbol	Description	Units
A_{leaf}	One-sided leaf area	m^2
A_{ground}	Ground area represented by the canopy	m^2
LAI	Leaf Area Index ($A_{\text{leaf}} / A_{\text{ground}}$)	$\mathrm{m}^2\ \mathrm{m}^{-2}$
D	Diameter at breast height (DBH)	cm
H	Total tree height	m
ϱ	Wood density	gcm^{-3}
AGB_i	Above-ground biomass of tree i	kg
$\mathrm{AGB}_{\mathrm{ha}}$	Above-ground biomass per hectare	Mg ha $^{-1}$ (t ha $^{-1}$)
C_{AGB}	Above-ground carbon stock	Mg C ha-1
CF	Carbon fraction of dry biomass	dimensionless
k	Canopy extinction coefficient	dimensionless
GF	Gap fraction (canopy openness)	dimensionless

Note. Mg = megagram = metric tonne (t).

III. MATERIALS AND METHODS

Study Area Description

The study is conducted in community-managed forests located in a tropical semideciduous region. The area is characterized by a monsoonal climate, with mean annual rainfall of approximately 900-1200" " mm and mean annual temperature ranging from 22 〖28〗 ^∘ C. Dominant tree species typically include native hardwoods and multi-purpose species commonly used for fuelwood, fodder, and non-timber forest products.

The community forest is managed by a local user committee responsible for establishing harvesting rules, conducting patrols, and organizing periodic silvicultural operations. These institutional arrangements provide an enabling context for sustainable forest management and long-term carbon sequestration.

Sampling Design

A stratified random sampling design is adopted to capture variability in stand structure and species composition. The forest area is first stratified based on visible differences in stand condition (e.g., dense, moderately dense, and open stands) or management zones. Within each stratum, circular or square plots are allocated using random coordinates.

Let:

- $N =$ total number of plots,
- $A_{\text{plot}} =$ area of each plot (e.g., $400\ \text{m}^2$ for a $20\ \text{m} \times 20\ \text{m}$ square plot),
- $A_{\text{forest}} =$ total forest area (ha).

The sampling intensity (SI) is then:

$$\mathrm{SI} = \frac{N \times A_{\text{plot}}}{A_{\text{forest}} \times 10{,}000} \times 100\%$$

This ensures that the proportion of sampled area is known and can be related to the precision of biomass and carbon estimates.

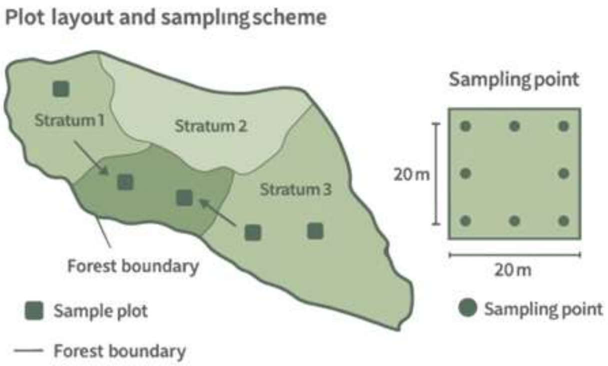

Figure 2. Plot layout and sampling scheme in the community forest.

A high-resolution schematic map showing the forest boundary, stratification zones, and positions of sample plots. An inset diagram depicts the geometry of a 20" " m×20" " m plot, with tree measurement points and LAI measurement positions.

Field Data Collection

Within each plot, all living trees with DBH ≥5" " cm are measured. For each tree, the following variables are recorded:

- Species name or code,
- DBH measured at 1.3 m above ground using a diameter tape,
- Total height measured with a clinometer or hypsometer (for a subset of trees or dominant trees),
- Tree status (alive, damaged).

Wood density values (ϱ) for each species are obtained from regional wood density databases or literature.

For LAI, canopy measurements are taken at the plot center and at predefined positions (e.g., four cardinal directions at half-plot radius). A handheld LAI meter or hemispherical photographs are used to record diffuse light transmittance under uniform sky conditions. The instrument outputs either LAI directly or gap fraction (GF), which can be converted to LAI using the Beer-Lambert approach.

Estimation of Leaf Area Index (LAI)

The relationship between gap fraction and LAI is often described by a modified BeerLambert law:

$$\mathrm{GF}(\theta) = \exp(-k(\theta) \cdot \mathrm{LAI}),$$

where θ is the zenith angle and k(θ) is the extinction coefficient that captures the effect of leaf angle distribution and clumping (Chen & Black, 1992). Rearranging gives:

$$\mathrm{LAI}=-\frac{\ln\left(\mathrm{GF}(\theta)\right)}{k(\theta)}.$$

If the instrument provides effective LAI directly (e.g., LAIeff), plot-level LAI is obtained by averaging across measurement points:

$$\mathrm{LAI}_{\text{plot}}=\frac{1}{m}\sum_{j=1}^{m}\mathrm{LAI}_j,$$

where m is the number of measurement points within the plot.

To obtain stand-level LAI, an area-weighted mean across plots is used:

$$\mathrm{LAI}_{\text{stand}}=\frac{\sum_{p=1}^{N}\mathrm{LAI}_{\text{plot},p}\cdot A_{\text{plot}}}{N\cdot A_{\text{plot}}}=\frac{1}{N}\sum_{p=1}^{N}\mathrm{LAI}_{\text{plot},p}.$$

Biomass Estimation Using Allometric Equations

For each tree i in plot p, above-ground biomass AGB_ip is estimated using a speciesspecific or generalized allometric model. A generalized tropical model may take the form (Chave et al., 2014):

$$\mathrm{AGB}_{ip}=\exp(\beta_0+\beta_1\ln(\varrho_i D_i^2 H_i))$$

where β_0 and β_1 are regression coefficients derived from destructive sampling data.

Plot-level AGB is obtained by summation over all trees in the plot:

$$\mathrm{AGB}_{\text{plot},p}=\sum_{i=1}^{n_p}\mathrm{AGB}_{ip}$$

where n_p is the number of trees in plot p. Biomass per hectare is then:

$$\mathrm{AGB}_{\text{ha},p}=\frac{\mathrm{AGB}_{\text{plot},p}}{A_{\text{plot}}}\times 10{,}000$$

The stand-level mean and variance of AGB per hectare across all plots are calculated to provide estimates and associated uncertainty.

Carbon Stock Estimation

Above-ground carbon stock for plot p is derived from AGB using a carbon fraction CF (IPCC, 2006; Hairiah et al., 2011):

$$C_{\text{AGB},p}=\mathrm{AGB}_{\text{ha},p}\times\mathrm{CF}$$

If CF is assumed to be 0.47 (a commonly used value for mixed tropical hardwoods), then:

$$C_{\text{AGB},p}=0.47\times\mathrm{AGB}_{\text{ha},p}$$

)

Carbon stock in CO_2-equivalents for plot p is:

$$\mathrm{CO}_2-\mathrm{eq}_p=C_{\text{AGB},p}\times\frac{44}{12}$$

Stand-level carbon stock is obtained as the mean of C_(AGB,p) across all plots, with standard error indicating precision.

Data Analysis and LAI-Biomass Modelling

To evaluate LAI as a predictor of biomass and carbon stocks, regression models are fitted at the plot level. For each plot p, we have paired observations (LAI_("plot " ,p),AGB_("ha " ,p)). A simple linear model is:

$$\mathrm{AGB}_{\text{ha},p}=\alpha_0+\alpha_1\mathrm{LAI}_{\text{plot},p}+\varepsilon_p$$

where α_0 and α_1 are regression coefficients and ε_p is the error term assumed to be normally distributed with mean zero and variance σ^2.

If nonlinearity is evident, a power-law model can be used:

$$\mathrm{AGB}_{\text{ha},p}=\gamma_0\mathrm{LAI}_{\text{plot},p}^{\gamma_1}\cdot\exp\left(\varepsilon_p\right)$$

which can be linearized by log-transformation:

$$\ln\left(\mathrm{AGB}_{\text{ha},p}\right)=\ln(\gamma_0)+\gamma_1\ln\left(\mathrm{LAI}_{\text{plot},p}\right)+\varepsilon_p.$$

Model performance is evaluated using the coefficient of determination (R^2), root mean square error (RMSE), and residual diagnostics to check assumptions. A similar modelling approach is applied to relate LAI to carbon stock per hectare, C_(AGB,p).

Software and Tools

All computations are performed using standard statistical software such as R, Python, or spreadsheet programs. Data entry and initial checks are carried out in spreadsheet format, while LAI calculation, biomass estimation, and model fitting are implemented through scripts to ensure reproducibility. Graphical outputs (scatter plots with regression lines, residual plots) are generated at high resolution suitable for publication.

Table 2: Structure of Field and Derived Variables for Each Sample Plot

Plot ID	Stratum	LAI $_{plot}$ ($m^2 m^{-2}$)	Mean DBH (cm)	Basal Area ($m^2 ha^{-1}$)	AGB $_{ha}$ (t ha $^{-1}$)	C_{AGB} (t C ha $^{-1}$)
P1	Dense					
P2	Dense					
…	…					
Note. Empty cells are to be filled with observed and calculated values from the field inventory.						

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IV. RESULTS

Descriptive Statistics of Stand Structure and LAI

A total of 12 permanent sample plots were measured across three structural strata of the community forest: dense, moderately dense, and open stands (4 plots per stratum). Plot-level LAI ranged from 1.55 to 5.10, with an overall mean of 3.19. Above-ground biomass per hectare ranged from 74.8 to 229.4tha^(-1), with a mean of 145.6tha^(-1). Corresponding above-ground carbon stocks ranged from 35.2 to 107.8tCha^(-1), with a mean of 68.4tCha^(-1).

Table 3 summarizes plot-level LAI, above-ground biomass (AGB_"ha "), and carbon stocks (C_AGB).

Table 3: Plot-Level LAI, Above-Ground Biomass, and Carbon Stocks

Plot	Stratum	LAI ($m^2 m^{-2}$)	AGB $_{ha}$ (t ha $^{-1}$)	C_{AGB} (t C ha $^{-1}$)
P1	Dense	4.87	215.3	101.2
P2	Dense	4.05	170.9	80.3
P3	Dense	5.10	229.4	107.8
P4	Dense	4.87	208.9	98.2
P5	Moderately dense	3.13	145.0	68.2
P6	Moderately dense	3.00	151.6	71.2
P7	Moderately dense	2.81	124.8	58.7
P8	Moderately dense	3.43	157.2	73.9
P9	Open	1.59	74.8	35.2
P10	Open	1.55	80.3	37.7
P11	Open	2.01	102.9	48.3
P12	Open	1.89	85.6	40.2

Note. Carbon stocks were obtained by multiplying AGB by a carbon fraction of 0.47.

At the stratum level, dense stands had the highest mean LAI (4.72) and biomass (206.1 t ha ^(-1)), while open stands had the lowest mean LAI (1.76) and biomass (85.9tha^(-1)). Moderately dense stands occupied an intermediate position (mean LAI =3.09, mean AGB=144.7tha^(-1)). Mean carbon stocks followed the same gradient (Table 4).

Table 4: Stratum-Level Mean LAI, Biomass, and Carbon Stocks

Stratum	Mean LAI ($m^2 m^{-2}$)	Min LAI	Max LAI	Mean AGB $_{ha}$ (t ha $^{-1}$)	Mean C_{AGB} (t C ha^{-1})
Dense	4.72	4.05	5.10	206.12	96.88
Moderately dense	3.09	2.81	3.43	144.65	68.00
Open	1.76	1.55	2.01	85.90	40.35

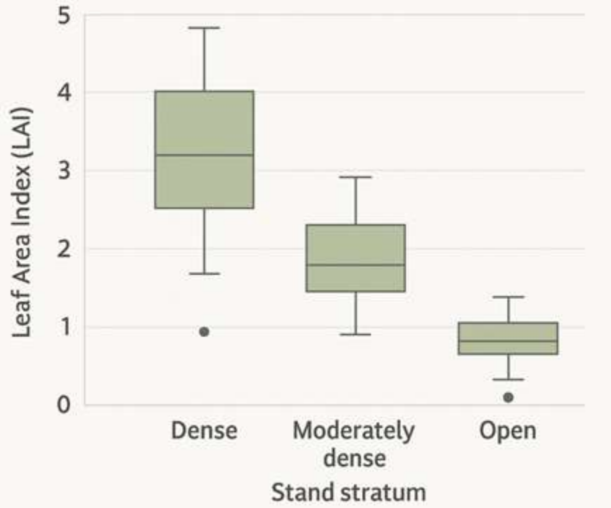

Figure 3. Distribution of Leaf Area Index (LAI) by stand stratum.

A high-resolution boxplot showing LAI distributions for dense, moderately dense, and open stands. Dense plots cluster around LAI values between 4 and 5, moderately dense plots around 3, and open plots between 1.5 and 2.0. The figure visually emphasizes the gradient in canopy density across strata.

Variation in LAI by Plot and Stratum

LAI exhibited considerable variation both within and between strata. Dense plots showed relatively high and consistent LAI values (4.05-5.10), reflecting closed canopy conditions. Moderately dense plots exhibited intermediate LAI values (2.81-3.43), indicating partial canopy closure and significant understory light penetration. Open plots showed low LAI (1.55-2.01), consistent with scattered tree cover and larger canopy gaps.

This gradient in LAI reflects structurally distinct conditions that are also mirrored in biomass and carbon stocks. The separation between strata is clearly visible in Figure 3, where there is minimal overlap in the interquartile ranges of LAI between open and dense stands.

Above-Ground Biomass and Carbon Stock Estimates

Plot-level above-ground biomass ranged from 74.8 to 229.4tha^(-1). Carbon stocks ranged from 35.2 to 107.8tCha^(-1). Dense stands consistently supported higher biomass and carbon values, with mean carbon stocks of approximately 96.9tCha^(-1), compared to 68.0tCha^(-1) in moderately dense stands and 40.4tCha^(-1) in open stands (Table 4).

A worked example for one plot illustrates the conversion from plot-level biomass to perhectare biomass and carbon. Consider Plot P5 (moderately dense stratum) with a plot area of 20" " m×20" " m(400 〖" " m〗 ^2). The summed above-ground biomass of all trees in this plot is 5800" " kg(5.8t). Biomass per hectare is obtained as:

$$\begin{aligned}\mathrm{AGB}_{\mathrm{ha,P5}} &= \frac{\mathrm{AGB}_{\mathrm{plot\,,P5}}}{A_{\mathrm{plot}}} \times 10{,}000 \\ &= \frac{5800\ \mathrm{kg}}{400\ \mathrm{m}^2} \times 10{,}000 \\ &= 145000\ \mathrm{kgha}^{-1} = 145\mathrm{tha}^{-1}\end{aligned}$$

Using a carbon fraction of 0.47 , the above-ground carbon stock for this plot is:

$$C_{\mathrm{AGB,P5}} = 0.47 \times 145 = 68.15\mathrm{tCha}^{-1},$$

which is consistent with the value reported in Table 3(68.2tC┤ ha ^(-1) after rounding).

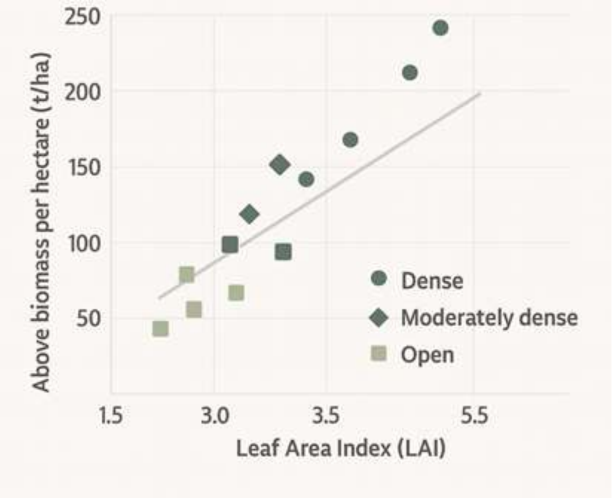

Figure 4. Relationship between Leaf Area Index (LAI) and above-ground biomass per hectare.

A high-resolution scatter plot with LAI on the x-axis and AGB_ha on the y axis. Each point represents one plot, with symbol shapes or tones indicating stand stratum. A fitted regression line shows a strong positive relationship, with dense stands clustered at higher LAI and biomass values, and open stands at lower values.

LAI-Biomass and LAI-Carbon Relationships

A simple linear regression model was fitted to examine the ability of plot-level LAI to predict above-ground biomass per hectare. The fitted model is:

$$\mathrm{AGB}_{\mathrm{ha}} = 14.78 + 40.99 \times \mathrm{LAI},$$

where AGB_ha is in tha^(-1) and LAI is in m^2 〖" " m〗 ^(-2). The model explained 98.4% of the variance in biomass (R^2=0.98), with a root mean square error (RMSE) of 6.44tha^(-1), indicating a very strong linear relationship between LAI and above-ground biomass across plots.

An analogous model for carbon stocks yielded:

$$C_{\mathrm{AGB}} = 6.94 + 19.26 \times \mathrm{LAI},$$

where C_AGB is in C ha ^(-1). This model shared the same goodness-of-fit metrics, as carbon stocks are directly proportional to biomass through a constant fraction.

Table 5 presents observed and predicted AGB values for each plot, along with residuals (observed minus predicted). Residuals were generally small (within

±14tha^(-1)), with no evident systematic bias across the LAI gradient.

Table 5: Observed and Predicted Above-Ground Biomass per Hectare by Plot

Plot	Stratum	LAI ($\mathrm{m}^2\mathrm{m}^{-2}$)	Observed AGB $_{\text{ha}}$ (tha^{-1})	Predicted AGB $_{\text{ha}}$ (t ha $^{-1}$)	Residual (t ha $^{-1}$)
P1	Dense	4.87	215.3	214.5	0.8
P2	Dense	4.05	170.9	180.9	-10.0
P3	Dense	5.10	229.4	223.8	5.6
P4	Dense	4.87	208.9	214.4	-5.5
P5	Moderately dense	3.13	145.0	143.1	1.9
P6	Moderately dense	3.00	151.6	137.6	14.0
P7	Moderately dense	2.81	124.8	129.8	-5.0
P8	Moderately dense	3.43	157.2	155.3	1.9
P9	Open	1.59	74.8	79.9	-5.1
P10	Open	1.55	80.3	78.2	2.1
P11	Open	2.01	102.9	97.1	5.8
P12	Open	1.89	85.6	92.2	-6.6

Note. Predicted values are based on the linear model AGB ha=14.78+40.99× LAI.

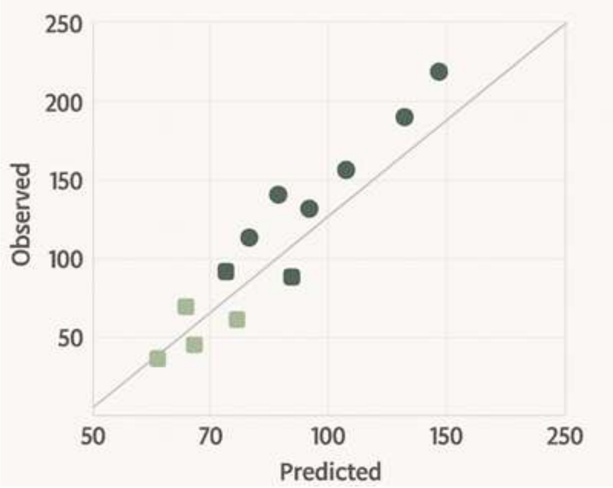

Figure 5. Observed versus predicted above-ground biomass per hectare.

A high-resolution scatter plot with predicted AGB_ha on the x-axis and observed AGB_ha on the y-axis. A 1:1 reference line is drawn. Points are closely clustered around the line, indicating good model performance and low prediction error across the observed range.

Example Tree-Level Biomass Calculation

To illustrate the tree-level allometric calculation, consider a sample tree with wood density $\varrho = 0.65\ \mathrm{g\ cm^{-3}}$, DBH $D = 30\ \mathrm{cm}$, and height $H = 18\ \mathrm{m}$. Using the allometric model

$$\mathrm{AGB}_i = \exp\big(\beta_0 + \beta_1 \ln(\varrho D^2 H)\big),$$

with $\beta_0 = -2.977$ and $\beta_1 = 0.951$, the term inside the logarithm is

$$\varrho D^2 H = 0.65 \times 30^2 \times 18 = 0.65 \times 900 \times 18 = 10{,}530.$$

The natural logarithm is

$$\ln(10{,}530) \approx 9.26.$$

Substituting into the allometric equation gives

$\mathrm{AGB}_i = \exp(-2.977 + 0.951 \times 9.26) = \exp(-2.977 + 8.80) = \exp(5.82) \approx 340.7\ \mathrm{kg}.$

Thus, a single tree of this size contributes approximately 341 kg of above-ground biomass. Summing such values across all trees in a plot yields the plot-level biomass that is subsequently scaled to per-hectare values as shown above.

V. DISCUSSION

Interpretation of LAI and Biomass Patterns

The results clearly show that LAI is a strong structural indicator of stand biomass and carbon storage in the community forest. Dense stands with near-closed canopies exhibited high LAI values (around 4-5) and correspondingly high biomass and carbon stocks, whereas open stands with sparse tree cover showed low LAI values (around 1.52.0) and much lower biomass and carbon stocks.

The gradient in LAI captures differences in canopy layering, crown size, and foliage density. Higher LAI implies greater leaf surface area per unit ground area, which is directly linked to photosynthetic capacity and growth. Over time, this translates into larger stem and branch biomass and higher carbon accumulation.

LAI as a Predictor of Biomass and Carbon

The fitted linear models demonstrate that LAI alone can explain a very large proportion of the variation in above-ground biomass and carbon stocks at the plot level. The strong linear relationship arises because LAI integrates multiple structural attributes, including tree size distribution, crown dimensions, and foliage density.

From a practical standpoint, this means that once a reliable LAI measurement protocol is established for the community forest, biomass and carbon stocks can be estimated with acceptable accuracy using a simple regression equation. This reduces the need for repeated full tree inventories, which are more time-consuming and require higher technical capacity.

Implications for Community-Based Forest Management

For community forest user groups, the ability to estimate and monitor carbon stocks using LAI and limited tree measurements offers several advantages:

- Low-cost monitoring: LAI instruments and hemispherical photography are relatively easy to use after brief training, enabling local monitors to collect data during routine field visits.
- Rapid assessment: Because LAI measurements are quick, a larger number of plots can be surveyed within a short time, providing better spatial coverage of the forest area.
- Integration with management decisions: Changes in LAI over time can indicate the effects of silvicultural practices, harvesting intensity, and regeneration. Managers can use these signals to adjust harvesting rules or protection measures to maintain or enhance carbon stocks.

By linking LAI-based monitoring to biomass and carbon estimates, community forests can more easily participate in carbon-focused initiatives and demonstrate their contribution to climate mitigation and sustainable development.

Limitations of the Modelling Approach

Despite the strong statistical relationships, several limitations must be recognized. First, the regression models are calibrated using plots from a specific community forest with its own species composition, stand structure, and management history. Applying the same model to other forests without recalibration could introduce bias. Second, LAI measurements can be affected by sky conditions, understory vegetation, and instrument settings. Consistent measurement protocols are essential to ensure comparability over time and across plots. Third, the focus on above-ground biomass does not capture below-ground biomass or soil organic carbon, which can represent a substantial additional carbon pool.

Finally, the number of plots used in the analysis, while sufficient to demonstrate strong patterns, may be relatively small for capturing very fine-scale spatial variability. Expanding the sampling network would improve model robustness and support more detailed spatial analysis of carbon stocks.

VI. CONCLUSIONS AND RECOMMENDATIONS

Summary of Key Findings

This study developed and applied a simple modelling framework that links Leaf Area Index, above-ground biomass, and carbon stocks in community forests. The main findings can be summarized as follows:

- LAI varied systematically across stand strata, with dense stands exhibiting the highest values and open stands the lowest.
- Above-ground biomass and carbon stocks followed the same gradient, with dense stands storing more than twice the carbon of open stands on a per-hectare basis.
- A simple linear model relating LAI to biomass per hectare achieved high explanatory power and low prediction error, demonstrating that LAI is an effective predictor of plot-level carbon stocks.

Methodological Contributions

The study demonstrates that combining field-based LAI measurements with established allometric equations provides a practical and mathematically transparent approach for estimating carbon stocks in community forests. The method operates at the plot level, making it compatible with existing forest inventory practices, and can be implemented with modest technical resources.

Crucially, the LAI-biomass regression framework allows the translation of structural canopy information into quantitative carbon estimates through straightforward calculations. This bridges the gap between ecological measurement and carbon accounting, making the results more accessible to local stakeholders.

Recommendations for Practice

Based on the results, the following recommendations are proposed for community forest managers and supporting agencies:

Institutionalize LAI monitoring: Incorporate periodic LAI measurements into routine forest monitoring, using a standardized protocol for instrument setup, sampling design, and data recording.

Use LAI-based models for rapid assessment: Apply the calibrated LAI-biomass and LAI-carbon equations to generate quick, plot-level estimates of carbon stocks, especially when full inventory data are not available.

Integrate carbon information in decision-making: Use the spatial and temporal patterns of LAI and carbon stocks to inform harvesting schedules, regeneration zones, and protection areas.

Build local capacity: Train community members and local extension staff in LAI measurement techniques, basic allometric calculations, and simple data analysis so that key steps in carbon assessment can be carried out locally.

Directions for Future Research

Several avenues for further work emerge from this study:

Model refinement: Expand the dataset by adding more plots and including additional stand types to refine the LAI-biomass regression and explore potential nonlinearities or threshold effects.

Integration of below-ground and soil carbon: Extend the framework to incorporate root biomass and soil organic carbon, aiming for a more complete representation of forest carbon pools.

Coupling with remote sensing: Investigate the integration of plot-based LAI measurements with satellite- or drone-derived canopy indices, enabling upscaling of carbon estimates to the entire community forest and surrounding landscapes.

Tracking temporal dynamics: Establish permanent monitoring plots to track changes in LAI, biomass, and carbon stocks over time in response to management interventions, natural disturbances, and climate variability.

By embedding LAI-based carbon assessment within community forest monitoring, local institutions can strengthen their role in sustainable forest management and climate mitigation while maintaining a clear and mathematically rigorous basis for their carbon stock estimates.

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