METHODOLOGICAL BASIS AND METHODS FOR ESTIMATING CARBON STOCKS IN AFOLU PROJECTS

VERSION 1.0

CERTIFICATION PROGRAM

TERO CARBON AVALIAÇÕES E CERTIFICAÇÕES S.A.

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LIST OF ACRONYMS

AGB	Above-Ground Biomass
AFOLU	Agriculture, Forestry, and Other Land Uses
ANOVA	Analysis of Variance
BGB	Below-Ground Biomass
CBH	Circumference at Breast Height
DAB	Diameter at Base
DBH	Diameter at Breast Height
PDD	Project Design Document
EVI	Enhanced Vegetation Index
IF	Inventário Florestal
INPA	National Institute for Amazonian Research, in Portuguese, *Instituto Nacional de Pesquisas da Amazônia*
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
MRV	Measurement, Reporting, and Verification
NBS	Nature-based Solutions
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
REDD+	Reducing Emissions from Deforestation and Forest Degradation, including the conservation and enhancement of carbon stocks
SAR	Synthetic Aperture Radar
VVB	Validation/Verification Body

LIST OF PROGRAMS

Certification Program
Methodologies Program
Assets Program

LIST OF SUPPORTING DOCUMENTS

NAME	PROGRAM
Definitions	All

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1. INTRODUCTION

The **Methodological Basis and Methods for Estimating Carbon Stocks in AFOLU Projects** were structured to ensure the environmental integrity, transparency, and credibility of certified carbon credits and stocks. In AFOLU (Agriculture, Forestry, and Other Land Use) projects, accuracy in estimating biomass and carbon stocks is a central element to ensuring the robustness of environmental assets and strengthening market confidence. Proper Measurement, Reporting, and Verification (MRV) of carbon stocks is essential to guarantee the traceability of results and alignment with international best practices, such as the guidelines of the Intergovernmental Panel on Climate Change (IPCC).

The IPCC defines three methodological levels—known as **Tiers**—for carbon quantification, varying in complexity, cost, and accuracy:

- **Tier 1** – Uses standard emission factors and generic data available in scientific literature, without requiring local data. It is the simplest and most accessible method but has higher uncertainty in estimates.
- **Tier 2** – Adopts region- or project-specific emission factors and incorporates local data to improve calculation accuracy.
- **Tier 3** – Employs advanced models, time series data, detailed forest inventories, and dynamic monitoring systems, combining field data with geospatial analyses.

Tero Carbon adopts **Tier 3 as the standard** for certifying environmental assets, ensuring the highest level of precision and integrity for carbon credits. This level requires integrating field data with advanced geoprocessing techniques—such as satellite imagery, LiDAR, and other technologies—to extrapolate results and monitor stocks over time.

However, in line with its commitment to expanding access for small projects to the global carbon market, Tero Carbon also accepts methods that rely exclusively on geoprocessing, provided that the software used is properly calibrated with field data and approved by Tero Carbon. This approach, while simplified compared to full Tier 3, enables smaller-scale projects to access the market **without compromising asset integrity**.

Developers opting for **geoprocessing-based models** must:

- Submit their software for approval by Tero Carbon.

- Demonstrate the calibration methods and biomass compartments considered.
- Present uncertainty measures (e.g., standard deviation and confidence interval).
- Provide a technical document (in Portuguese and English) with general details of the method, ensuring transparency while safeguarding proprietary information.

During the **validation phase**, Tero Carbon will accept results generated by the submitted models. However, during **verification**, an **on-site audit** with field data collection will be conducted to compare estimated data and ensure compliance with the reported results.

This methodological guide serves as a reference for project developers, consultants, independent verifiers, and other stakeholders involved in quantifying carbon stocks in AFOLU projects. By establishing clear guidelines aligned with **IPCC Tiers**, Tero Carbon strengthens **transparency, traceability, and integrity** in certified credits, reinforcing its mission to broaden access to the global carbon market for projects of all scales.

2. ESTIMATION OF BIOMASS AND CARBON STOCKS: INTEGRATION OF FIELD DATA AND REMOTE SENSING (TIER 3)

The **Tier 3** method, as established by the **IPCC (2006) guidelines**, represents the **highest level of accuracy** for biomass and carbon estimates. It is characterized by the use of **advanced models, time-series data, and the integration of field-collected data with remote sensing techniques**. **Tero Carbon** adopts Tier 3 as the standard for the certification of environmental assets due to its methodological robustness and ability to reflect the real dynamics of carbon stocks in **AFOLU (Agriculture, Forestry, and Other Land Use) projects**.

This chapter presents the **guidelines for applying Tier 3** within the **Certification Program – Nature-Based Solutions (NBS)**, establishing **minimum requirements for data collection, processing, analysis, and reporting**.

2.1. General Guidelines for Tier 3

The Tier 3 methodology requires the combination of multiple data sources and advanced techniques to ensure greater accuracy and precision in estimates. The process includes:

- **Field data collection** through qualitative and quantitative diagnostics (forest or agricultural inventories), considering aspects such as aboveground, belowground (roots), and litter biomass (when applicable).
- **Georeferencing of sample units and points** with a minimum accuracy of 10 meters, ensuring correct alignment with remote sensing images.
- **Remote sensing**, using satellite imagery, LiDAR, drones, or Synthetic Aperture Radar (SAR) to expand monitoring scale and frequency.
- **Statistical and geospatial models** for extrapolating field data, enabling spatial analyses and reducing uncertainties.

This integration allows for monitoring the spatial and temporal variation of carbon stocks, improving accuracy and reducing uncertainty in estimates.

2.2. Field Data Collection

The field stage is essential for calibrating remote sensing models and must follow rigorous protocols.

2.2.1. Definition of Sampling Units

Sampling units (fixed or variable area plots) must be randomly and/or systematically allocated to capture the variability of the studied area. Recommended practices include:

- Installing **permanent and/or temporary sampling units**, properly georeferenced with precision (5 to 10 meters error margin).
- Determining the number of sampling units based on the heterogeneity of the area and biomass density:
  - For normally distributed populations, a minimum of three (3) sampling units per stratum;

  - For non-normally distributed populations, a minimum of thirty (30) sampling units per stratum.

Important: The larger the sampling size (greater number of sampling units), the lower the sampling error (higher precision).

2.2.2. Measured Parameters

During data collection, fundamental parameters must be recorded to ensure robust biomass and carbon estimates:

- **Diameters:**
  - Diameter at 1.3m from the ground (DBH), when applicable;
  - Base diameter (DAB - Diameter at Base), when applicable;
  - Canopy diameter (DCopa - Canopy Diameter), when applicable.
- **Heights:**
  - Total height, from the base of the plant to its highest point;
  - Trunk/stem height, from the base to the start of the canopy (when applicable).
- **Other Parameters:**
  - Espécie botânica (ou grupo funcional, quando aplicável);
  - Densidade da madeira (quando aplicável).

2.2.3. Biomass Calculation

Field-collected data are used as inputs for allometric equations to estimate biomass. These equations may be:

- Regional or project-specific, considering local environmental factors.
- Applied to different compartments, such as aboveground biomass, belowground biomass, and litter, among others.

2.3. Integration with Remote Sensing

The use of remote sensing technologies enhances the spatial and temporal coverage of biomass and carbon estimates, enabling detailed mapping and periodic updates.

2.3.1. Image Acquisition and Processing

To ensure data quality, rigorous image processing is essential. The steps include:

- **Selecting appropriate sensors**, such as **LiDAR** for structural data, **multispectral imagery** (e.g., **Sentinel-2, Landsat 8**), and **radar (Sentinel-1)** for dense canopy coverage.
- **Applying geometric and radiometric corrections** to ensure spatial alignment and standardization of the data.

2.3.2. Model Calibration

Calibrating predictive models is a critical step to ensure the accuracy of estimates. The process involves:

- Correlating remote sensing-derived variables (e.g., NDVI, canopy height) with field data.
- Applying statistical and machine learning techniques (e.g., multiple regression, random forest) to build robust models.
- Accessing real biomass data (fresh and/or dry weight), determined through destructive sampling or estimated using specific allometric equations.

2.3.3. Extrapolation and Mapping

After calibration, the models are applied across the entire project area to generate continuous biomass and carbon maps. The steps include:

- Creating thematic maps at scales compatible with the project scope.
- Calculating uncertainty levels and confidence intervals for all estimates.

2.4. Validation and Verification

The quality of results must be ensured through rigorous validation and verification processes.

- **Internal validation** must be conducted by the **Developer** before submitting data for certification, using **independent sample plots** different from those used in calibration.
- **External verification** includes **field visits** carried out by **Tero Carbon auditors** (Verification Body - **VVB**), who collect data to compare with the model results.
- If **uncertainties exceed permissible limits**, **methodological adjustments** must be applied.

2.5. Documentation Requirements

To ensure traceability and transparency, the developer must provide:

- A detailed technical report describing all steps of the applied method;
- A breakdown of the calibration and validation process;
- A specification of the biomass compartments considered;
- Uncertainty parameters (e.g., standard deviation, confidence interval);
- A Project Design Document (PDD) (PT/EN) explaining the methodology in accessible language, ensuring transparency without disclosing sensitive information.

3. BIOMASS AND CARBON STOCK ESTIMATION: REMOTE SENSING-ONLY METHODS (TIER-2)

The use of **remote sensing technologies** for biomass and carbon stock estimation represents a practical and scalable alternative for projects facing resource limitations that prevent extensive field data collection. These methods enable the analysis of large geographical areas, optimizing both time and operational costs. However, due to the absence of field data in the initial process, it is crucial that the models used are calibrated based on existing data and subjected to rigorous approval processes.

Tero Carbon adopts **Tier 3** as the standard for the certification of environmental assets. However, to increase access to the carbon market and support small-scale projects, it also recognizes remote sensing-only methods, provided that they are approved and include clear calibration and validation procedures.

3.1. General Guidelines for Remote Sensing Methods

Remote sensing-based methods must ensure the technical robustness of estimates, minimizing uncertainties and promoting transparency in results. The basic guidelines include:

- Use of high-resolution spatial and temporal imagery.
- Calibration of predictive models using existing field data or reliable secondary data.
- Establishment of uncertainty metrics, such as standard deviation and confidence intervals.
- Possibility of auditing and verifying results by independent entities.

3.2. Data Sources and Technologies

Remote sensing techniques enable the extraction of spatial and temporal information about vegetation, allowing for the estimation of biomass stocks based on observable parameters in the images. The main data sources include:

- **Optical Satellites (e.g., Sentinel-2, Landsat):** Useful for monitoring vegetation (NDVI, EVI) in forests and agricultural landscapes.
- **LiDAR:** Technology that provides three-dimensional structural information about vegetation, enabling a more detailed biomass assessment.
- **Other Remote Sensing Technologies:** Use of hyperspectral sensors, radar, and drones, which can complement data analysis.
- **Auxiliary Data:** Integration with soil and climate information for more robust modeling.

3.3. Development of Accurate Models

The development of accurate models requires a rigorous calibration process. The developer must:

- Use public or private databases containing biomass information obtained from forest or agricultural inventories;
- Apply machine learning techniques (e.g., Random Forest, Neural Networks) to identify patterns between remote sensing data and biomass stocks;
- Define the biomass compartment being evaluated (e.g., aboveground live biomass, belowground biomass, litter) and ensure methodological consistency.

The models must include performance indicators (e.g., R^2, RMSE) and incorporate uncertainty measures.

3.4. Software Approval Process

All software used for biomass and carbon stock estimation must undergo **Tero Carbon's approval process**. The process includes:

- Submission of detailed technical documentation.
- Demonstration of the model calibration and validation process.
- Uncertainty analysis and assessment of the applied methodologies.
- Consistency tests conducted by technical auditors.

Only after successful approval can the software be used in certified projects.

3.5. Validation and Verification

Although field data collection is not required in the initial process, on-site verification remains mandatory during the certification phase. The external auditor contracted by Tero Carbon (**Validation and Verification Body — VVB**) will conduct field visits to:

- Collect field samples and compare them with the software's estimates.

- Assess whether the deviation between field data and estimated values falls within acceptable limits.
- Adjust the models, if necessary, in cases of significant discrepancies.

3.6. Transparency and Accessibility

Model and software developers must provide a public document (PT/EN) explaining the methodology used, ensuring clarity in the estimation process without disclosing sensitive details.

This transparency strengthens the integrity of certified environmental assets and increases the acceptance of carbon credits in the international market.

4.METHODOLOGICAL BASIS: BIOMASS COMPARTMENTS

Vegetal biomass has been one of the most discussed topics in recent years, particularly regarding its role in global climate change. According to the IPCC, forests, agriculture, and other systems that can absorb and store carbon are referred to as "sinks."

Biomass, or phytomass, is defined as the quantity (expressed in units of mass) of plant material per unit of area in a forest or plantation (Araújo et al., 1999). Therefore, vegetal biomass estimates are essential information in matters related to climate change, as they help estimate the carbon balance in the biosphere-atmosphere interaction (Higuchi, 2001).

Using water and carbon content, for example, the biomass of crops and forests can be converted into vegetation carbon, which is the primary variable considered in projects related to global climate change. However, little is known about the importance of biomass in agricultural crops, particularly coffee, and its role in ecosystem services.

Biomass is defined as the weight of a tree, expressed in kilograms (kg) for individual measurements or tons (t) for aggregated stocks (IPCC, 2006). In large-scale studies, such as regional or national biomass estimates—for example, in tropical regions or across the Amazon—biomass stocks are often presented in abbreviated units, following the IPCC (2006) standard:

- **Megagram (Mg) or Megaton (Mt)** for **millions of tons**;
- **Gigagram (Gg) or Gigaton (Gt)** for **billions of tons**;
- **Teragram (Tg) or Teraton (Tt)** for **trillions of tons**;
- **Petagram (Pg) or Petaton (Pt)** for **quadrillions of tons**.

According to the IPCC National Greenhouse Gas Inventory Guidelines, forest biomass is classified into three main compartments:

- **Aboveground biomass (AGB):** Includes trunk, branches, leaves, flowers, and fruits;
- **Belowground biomass (BGB):** Corresponds to the roots;
- **Total biomass:** Sum of aboveground and belowground biomass (AGB + BGB).

These divisions are fundamental for an accurate assessment of carbon stocks in AFOLU (Agriculture, Forestry, and Other Land Use) projects aimed at the carbon market.

For instance, Silva (2007) highlights that in trees from the Manaus region, approximately **41.6%** of the total weight corresponds to water. After drying, about **48.5%** of the dried mass consists of carbon. This means that, in the total weight of a living tree, approximately **40%** is water and **30%** is carbon—an essential piece of information for carbon stock calculations and the development of emission mitigation strategies.

5. METHODOLOGICAL BASIS: BIOMASS QUANTIFICATION

The quantification of total biomass—comprising both aboveground and belowground biomass—can be performed using either **direct** or **indirect methods**.

5.1. Direct (Destructive) Method

The direct method consists of cutting and weighing plant material within a predefined area. Although this method provides precise measurements for the assessed area, it has some limitations:

- **Sampling bias:** The selection of the area to be cut may not accurately represent the variability of the forest, leading to inaccurate estimates when extrapolated to larger scales.
- **High cost and environmental impact:** Besides being expensive, the method destroys the sampled vegetation, making continuous measurement of the same plants impossible.

Due to these limitations, the direct method is rarely used in large-scale carbon projects. Instead, it is mainly applied for calibrating indirect models.

5.2. Indirect (Non-Destructive) Method

The indirect method uses mathematical models to estimate the biomass of standing plants, relying on variables that are easily measurable in the field. These models are based on regression analyses and result in allometric equations (Higuchi & Carvalho, 1994).

5.2.1. Allometric Equations

The term allometry, from Greek origins (allos = "other," metron = "measure"), refers to the study of relationships between the size of different parts of an organism and the organism as a whole. In forestry and agronomy, allometry explores the correlation between tree structural characteristics—such as diameter, height, and canopy size—and its total biomass (Niklas, 1994).

Allometric equations for biomass estimation are often derived from models originally used for wood volume calculation (Santos, 1996). These equations typically have high coefficients of determination ($r^2 > 0.95$), indicating high accuracy. The most commonly used independent variables include:

- **Diameter at Breast Height (DBH)**—measured at 1.30 m above the ground;
- **Total tree height**.

One of the most well-known models is that proposed by West et al. (1999):

$$M = a * D^b$$

where:

M = aboveground dry biomass;

D = diameter at breast height (1.30 m above ground);

a = scaling coefficient; and

b = scaling exponent.

This model is based on the resource distribution theory in vascular plants, assuming a hierarchical branching system. Initially, it was believed that a universal exponent (multiples of ¼) applied to all plants. However, later studies showed that this regularity does not apply to all vegetation types (Zianis & Mencuccini, 2004; Pilli *et al.*, 2006). Despite this, the model remains widely used due to its simplicity and its ability to replace destructive methods.

5.3. Errors and Uncertainties in Biomass Estimation

When using the indirect method, it is essential to consider two main types of error:

- **Non-sampling errors:** These are related to failures during data collection (e.g., inaccurate measurements or improper sample selection). Such errors can be minimized through strict adherence to field procedures and proper application of methodological protocols. It is important to note that sophisticated statistical analyses cannot compensate for inadequately collected data.
- **Sampling errors:** These arise when only a fraction of the population is measured, introducing uncertainties into the estimates. In carbon projects, assessing the uncertainty associated with the estimated mean is as relevant as the mean itself. This uncertainty can be represented by a probability density function, indicating the variation and reliability of the obtained values.

The magnitude of uncertainty depends directly on the **quality** and **quantity** of collected data, as well as on the inference methods used.

5.4. Statistical Basis: Sampling and Uncertainty

Two fundamental theorems support statistical analysis applied to biomass quantification:

5.4.1. Law of Large Numbers

The **Law of Large Numbers** states that as the number of independent observations increases, the sample mean approaches the true population value. In practical terms:

> *"If an event with probability 'p' is observed repeatedly under independent conditions, the relative frequency of the event converges to 'p' as the number of repetitions becomes sufficiently large."*

Therefore, the larger the number of samples (**n ≥ 30**), the more reliable the estimated mean will be in relation to the true population value.

5.4.2. Central Limit Theorem

The **Central Limit Theorem** states that:

> *"If a random variable X can be represented as the sum of n independent random variables, under certain general conditions, this sum will have an approximately normal distribution for a sufficiently large n."*

This means that sample means tend to follow a normal distribution around the population mean, regardless of the original data distribution. As a result, classical statistical methods can be applied, and the **z-table** can be used to calculate probabilities, provided the sample size is adequate.

In a normal distribution:

- **68.27%** of the data lies within **±1 standard deviation** of the mean;
- **95.45%** lies within **±2 standard deviations**;
- **99.73%** lies within **±3 standard deviations**.

Therefore, increasing the number of samples reduces the standard deviation and improves the precision of the estimates.

6. METHODOLOGICAL BASIS: VARIABLES OF INTEREST

The quantification of carbon stock in tropical forests and agricultural crops depends on the analysis of different variables, which can be classified as **dependent** and **independent**.

- **Independent Variables** are those that are easy to measure, obtained directly in the field or through remote sensing tools and technologies. They serve as the basis for estimating dependent variables using allometric equations.
- **Dependent Variables** are those that are difficult or unfeasible to measure directly in the field and, therefore, must be estimated based on independent variables. These variables represent the main focus of biomass and carbon quantification projects.

Table 1 presents the key variables considered in estimating carbon stock in forest areas and agricultural crops.

Table 1. List of Variables Considered for Determining Carbon Stock in a Tropical Forest Area and Agricultural Crops.

VARIABLE NAME	TYPE	UNIT	DESCRIPTION
Crop area	Independent	Hectare (ha)	Basic unit for carbon estimates. 1 hectare = 10,000 m^2
Spectral reflectance	Independent	Nanometer (nm)	Data obtained through remote sensing for extrapolation of carbon stocks over large areas
Spatial resolutionl	Independent	Meter (m)	Pixel size in satellite images, indicating the level of surface detail (e.g., 30 cm provides more detail than 1 m)
Circumference or Diameter at Breast Height (CBH/DBH)	Independent	Centimeter (cm)	Trunk diameter measured at 1.30 m above ground. If physical obstacles exist, measurement can be taken at another height

VARIABLE NAME	TYPE	UNIT	DESCRIPTION
Total height (Ht) and commercial height (Hc)	Independent	Meter (m)	**Ht** is the height up to the top of the canopy; **Hc** refers to the usable trunk height up to the start of the canopy
Dominant height (Hdom)	Dependent	Meter (m)	Average height of the tallest 10% of individuals in a sample area
Correction factor (fc)	Dependent	-	Adjustment applied when the allometric equation was developed in areas with different structural characteristics from the studied area
Aboveground fresh biomass (BFabg)	Dependent	Ton (t)	Mass of the tree's aboveground portion (trunk, branches, leaves, flowers, fruits, and seeds), including water content
Belowground fresh biomass (BFblg)	Dependent	Ton (t)	Mass of the tree's root system, considering water content
Total fresh biomass (BFtot)	Dependent	Ton (t)	Sum of aboveground and belowground fresh biomass
Aboveground dry biomass (AGB)	Dependent	Ton (t)	Dry mass of the tree's aboveground portion after water removal
Belowground dry biomass (BGB)	Dependent	Ton (t)	Dry mass of the tree's roots, excluding water content
Total dry biomass (BStot)	Dependent	Ton (t)	Sum of aboveground and belowground dry biomass
Aboveground carbon (Cabg)	Dependent	Ton (t)	Amount of carbon stored in the tree's aboveground portion
Belowground carbon (Cblg)	Dependent	Ton (t)	Amount of carbon stored in the tree's roots

VARIABLE NAME	TYPE	UNIT	DESCRIPTION
Total carbon (Ctot)	Dependent	Ton (t)	Sum of carbon stored aboveground and belowground
Aboveground Carbon Dioxide Equivalent (CO_2e.abg)	Dependent	Ton (t)	Amount of aboveground carbon converted into carbon dioxide equivalent (CO_2e) using the standard conversion factor (1 t of C = 3.67 t of CO_2e)
Belowground Carbon Dioxide Equivalent (CO_2e.blg)	Dependent	Ton (t)	Amount of carbon in the roots converted into carbon dioxide equivalent
Total Carbon Dioxide Equivalent (CO_2e.tot)	Dependent	Ton (t)	Sum of carbon dioxide equivalent stored aboveground and belowground

The correct identification and use of the variables of interest are essential to ensuring accuracy in biomass and carbon stock estimates. Independent variables must be measured with technical precision so that dependent variables can be reliably calculated, reducing uncertainties in the results.

7. METHODOLOGICAL BASIS: STATISTICAL TOOLS

The quantification of biomass and carbon stocks in forests and agricultural crops requires the use of **statistical inference tools** to ensure result **accuracy and reduce uncertainties**. Statistics provide fundamental methods for data collection, analysis, and interpretation, enabling reliable estimates.

The following **Table 2** presents the main statistical parameters used, along with their descriptions and respective mathematical formulas.

Table 2. Statistical Parameters, Their Descriptions, and Mathematical Formulas.

PARAMETER	DESCRIPTION	FORMULA
Mean	Average value obtained by summing all observations and dividing by the total number of observations	$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n}$

PARAMETER	DESCRIPTION	FORMULA
Variance (s^2)	Measures data dispersion in relation to the mean. Calculated by summing squared deviations and dividing by the number of observations minus one	$s^2 = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}{n-1}$
Standard Deviation (s)	Square root of the variance. Indicates the degree of dispersion of values around the mean	$s = \pm\sqrt{s^2}$
Standard Error of the Mean ($s_{\bar{x}}$)	Measures the accuracy of the sample mean relative to the population mean. The smaller the standard error, the more representative the sample	$s_{\bar{x}} = \frac{s}{\sqrt{n}}$
Confidence Interval (IC)	Determines the range in which the population mean is expected to fall within a predefined confidence level (usually 95%)	$\bar{x} \pm z \times \frac{\sigma}{\sqrt{n}}$
Corrected Sum of Squares for variable Y (SQC_Y)	Measures the total variation of dependent variable values in relation to their mean	$CQC_y = \sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}$
Corrected Sum of Squares for variable X (SQC_X)	Measures the total variation of independent variable values in relation to their mean	$SQC_x = \sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}$
Corrected Sum of Products (SPC_{XY})	Measures the relationship between variations of the independent and dependent variables. Used in correlation coefficient calculation	$SPC_{xy} = \sum_{i=1}^{n} x_i y_i - \frac{\left(\sum x_i\right) \times \left(\sum y_i\right)}{n}$
Correlation Coefficient (r)	Evaluates the degree of linear association between independent and dependent variables. Ranges from -1 (negative correlation) to +1 (positive correlation)	$r = \frac{SPCxy}{\sqrt{SQC_x SQC_y}}$

7.1. Stratification

Stratification is a statistical technique aimed at reducing variance within groups (strata), increasing estimate accuracy, and optimizing the sampling process. In studies quantifying biomass and carbon stocks in forests or agricultural crops like coffee, stratification allows a more accurate representation of the spatial and structural heterogeneity of the study area.

There are two main methods for stratifying an agricultural crop or forest: by **data variance** or by **age/forest class**. The choice of method depends on site characteristics, study objectives, and available resources.

7.1.1. Stratification by Variance

This method uses preliminary data to define strata based on observed variability. Although straightforward, it has some limitations:

- **Requires preliminary sampling**, which may demand extra time and resources;
- **Low cost-benefit ratio**, especially in large or hard-to-access areas;
- **Risk of biased estimates** if the initial sampling does not adequately represent area variability.

This method is highly sensitive to non-representative samples, potentially compromising result accuracy.

7.1.2. Stratification by Age or Class

This method employs **remote sensing** and **geoprocessing technologies** to identify different strata based on structural characteristics, such as age or forest classes. The use of satellite images from different sensors—such as RGB and Near-Infrared (NIR) bands—enables a more detailed vegetation analysis.

Key advantages of this method include:

- **Optimized sampling** through more efficient prior planning;
- **Increased estimate reliability**, reducing uncertainty in results;

- **Long-term cost reduction**, minimizing the need for intensive field sampling.

The ability to identify spatial patterns via remote sensing makes this method more robust, especially in large areas or forests with high structural variability.

7.1.3. Statistical Validation of Stratification

Although remote sensing provides visual evidence of differences between age groups or forest classes, **statistical significance** must be verified. **Analysis of Variance (ANOVA)** is recommended to assess whether significant differences exist between strata means.

If ANOVA detects statistically significant variability, the stratification is considered valid. Otherwise, stratified sampling and statistical inference become unnecessary.

When ANOVA identifies relevant differences, a **post hoc test**, such as **Tukey's Test**, should be applied to compare strata and determine which groups show statistically significant differences.

7.1.4. Stratified Statistics

Mathematical formulas for stratified inference statistics, as presented by **Péllico Netto and Brena (1997)**, are shown in **Table 3**:

Table 3. Stratified Statistical Parameters, Their Descriptions, and Mathematical Formulas.

PARAMETER	DESCRIPTION	FORMULA
Mean per stratum	Arithmetic mean for each sampled stratum	$\bar{x}_h = \frac{\sum_{i=1}^{n_h} X_{ih}}{n_h}$
Stratified mean	Weighted mean based on sampled strata	$\bar{x}_{st} = \sum_{h=1}^{L} w_h \bar{x}_h$
Variance per stratum	Population variance for each sampled stratum	$s_h^2 = \frac{\sum_{i=1}^{n_h} \left(x_{ih} - \bar{x}_h\right)^2}{n_h - 1}$

PARAMETER	DESCRIPTION	FORMULA
Stratified variance	Population variance weighted by sampled strata	$s_{st}^2 = \sum_{h=1}^{L} w_h s_h^2$
Variance of the stratified mean	Weighted variance of the sampled population mean	$s_{\bar{x}_{(st)}}^2 = \sum_{h=1}^{L} w_h^2 \times \frac{s_h^2}{n_h}$
Stratified standard error	Weighted standard error of the sampled population	$s_{\bar{x}_{(st)}} = \sqrt{s_{\bar{x}_{(st)}}^2}$
Stratified sampling error	Weighted sampling error of the population inference estimate	$E_r = \pm \frac{t \times s_{\bar{x}_{(st)}}}{\bar{x}_{(st)}} \times 100$
Confidence Interval (95%)	Estimated mean variation range with a 95% probability	$I.C. = \bar{x} \pm z \times \frac{\sigma}{\sqrt{n}}$

8. METHODOLOGICAL BASIS: EXTRAPOLATION (SCALE UP)

Extrapolation — or scale up — is a process used to expand the estimates obtained from sample plots to larger areas, ensuring that local results can represent regional or even global landscapes. In the context of forest and agricultural inventories, such as coffee plantations and tropical forests, this process requires integrating field data with remote sensing technologies while adhering to technical criteria that ensure the accuracy and representativeness of estimates.

8.1. Georeferencing: The Foundation for Extrapolation

The starting point for an efficient extrapolation process is the **precise georeferencing** of trees and sample plots. Accurate spatial location allows the correlation of field data with remote sensor images across various mapping scales.

Several factors influence georeferencing quality:

- **Type of GPS equipment used** — different models offer significant variations in data accuracy;
- **Data collection procedures** — proper techniques minimize errors associated with positioning;

- **Satellite coverage available at the time of collection** — which may limit accuracy in areas with dense vegetation;
- **Forest cover** — areas with a closed canopy can affect the GPS signal, reducing the accuracy of coordinates (JUN; GUENSLER; OGLE, 2006; RODRÍGUEZ-PÉREZ; ÁLVAREZ; SANZABLANEDO, 2007; SIGRIST; COPPIN; HERMY, 1999).

8.2. Integration of Field Data and Remote Sensing

Extrapolation is only possible through the **integration of field data with satellite imagery or aerial photogrammetry**, which expands the area of analysis without requiring increased sampling effort. This integration depends directly on the spatial and spectral quality of the images used.

Two key factors influence this stage:

- **Spatial resolution** — The higher the resolution (i.e., the smaller the pixel), the more detailed the captured information. For carbon estimates, high-resolution images allow for more precise local-scale analyses, while lower-resolution images are better suited for regional analyses.
- **Mapping scale** — Choosing the appropriate scale influences extrapolation quality. Local maps require greater detail, while regional approaches can accept lower resolution as long as spatial patterns are preserved.

The combined use of **multi-sensor data** — such as optical, radar, and LiDAR images — is highly recommended to improve biomass and carbon estimates, as each sensor captures complementary landscape information (LU *et al.*, 2012).

8.3. From Local to Regional: Expanding Estimates

Data extrapolation is not limited to the local scale. By using remote sensing and advanced geoprocessing techniques, it is possible to expand analyses to regional and even national levels. However, this process requires strict control of **errors associated** with modeling and data interpretation (IPCC, 2010).

Studies by **Trumbore, Brando, and Hartmann (2015)** and **Zhang *et al.* (2014)** highlight the importance of multi-scale and multi-sensor approaches to obtaining reliable estimates in different forest and agricultural scenarios. Controlling errors during the scale-up process is essential to ensure that uncertainties remain within acceptable limits, especially when the data is used in public policies or carbon markets.

9. ALLOMETRY OF BIOMASS AND CARBON: TROPICAL FOREST

Forest **allometry** is a tool used to estimate biomass and carbon storage in tropical forests. Through allometric equations, it is possible to relate easily measurable field variables, such as diameter at breast height (DBH) and, in some cases, total height, to the total biomass of a tree. These equations eliminate the need for large-scale destructive methods, optimizing costs and preserving the environment.

Below are the main concepts, methods, and recommended equations for tropical forests, with emphasis on data from the **Tropical Silviculture Experimental Station (ZF2)** of **INPA**, located in Manaus, Amazonas.

9.1. Destructive Method: Basis for Allometric Equations

The classic method for developing allometric equations involves cutting down and **directly weighing** trees within fixed-area plots (**Figure 1**). After felling, trees are sectioned into different compartments — **canopy, trunk, and root system** — to facilitate weighing (SILVA, 2007). While this approach provides accurate data, it has significant limitations:

- **Low representativity** due to the limited number of sampled plots;
- **High cost and logistical complexity** in dense forest areas;
- **Environmental risk, given the destructive nature of the method.**

Figure 1. Images of Field Activities Using the Destructive Method for Determining Total Weight Above and Below the Soil of a Tree.

Despite these limitations, the destructive method remains the foundation for calibrating allometric equations widely accepted in scientific studies (ARAÚJO *et al*., 1999; SILVA, 2007; LIMA *et al*., 2012).

9.2. Allometric Equations for the Amazon: ZF2 (INPA)

In the Amazon, various studies have generated robust equations for biomass and carbon estimates. For tropical forests, Tero Carbon recommends using the equations developed for the **ZF2** site due to their extensive scientific validation and strong adherence to the precision standards required.

The suggested equations for tropical forests in the Manaus region are:

$BStot = 2.7179 \times DBH^{1.8774} \times 0.584 \times fc$, where $R^2 = 0.94$ e $Syx\% = 3.91$.

$AGB = 2.2737 \times DBH^{1.9156} \times 0.584 \times fc$, where $R^2 = 0.85$ e $Syx\% = 4.20$.

$BGB = 0.0469 \times DBH^{2.4754} \times 0.533 \times fc$, where $R^2 = 0.95$ e $Syx\% = 5.12$.

where:

$BStot$ = total dry biomass (Kg);

AGB = aboveground dry biomass (Kg);

BGB = belowground dry biomass (Kg);

DBH = diameter at breast height (cm);

fc = correction factor;

R^2 = coefficient of determination (fit quality); and

$Syx\%$ = standard error of the estimate (%).

9.3. Correction Factor (fc): Adaptation for Other Regions

If the project is developed in areas with structural characteristics different from those of the ZF2 site, applying a correction factor (**fc**) is recommended.

The **fc** adjusts the equations to reflect the vertical structure of the local forest and is calculated as the ratio between the dominant height of the sampled site (**$Hdom_i$**) and the dominant height of the ZF2 site (**HdomZF2 = 30.2 m**) using the formula:

$$fc = \frac{Hdom_i}{Hdom_{ZF2}}$$

where:

fc = correction factor;

$Hdom_i$ = estimated dominant height for the sampled site "i"; and

$Hdom_{ZF2}$ = dominant height of the ZF2 site = 30.2 m[1].

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[1] According to Higuchi (2015).

The dominant height (**Hdom**) is the average height of the 10% thickest trees in the sample, following the approach proposed by Higuchi (2015).

9.4. Biomass-to-Carbon Conversion

The biomass estimated by the equations must be converted into carbon using specific conversion factors, considering the different parts of the tree:

$$Cabg = AGB \times 0.485$$

$$Cblg = BGB \times 0.464$$

$$Ctot = Cabg + Cblg$$

where:

Cabg = carbono acima do solo (Kg);

Cblg = carbono abaixo do solo (Kg); e

Ctot = carbono total (Kg).

9.5. Note to Developers

- If the project takes place in a forest type different from the Manaus region, using **"site-specific" equations adjusted** from local data is recommended.
- The equations must follow Measurement, Reporting, and Verification (MRV) guidelines.
- The use of additional variables (e.g., wood density) may be considered if technically justified, but cost-benefit should be weighed.
- Including height as an independent variable is optional. Studies show that its incorporation does not significantly increase model accuracy in Amazonian forests while adding costs and increasing measurement errors (WIEMANN & WILLIAMSON, 2014).

9.6. Model Reliability

- The **adjusted coefficient of determination (R^2aj)** must be greater than **0.80** to ensure estimation robustness.
- The **standard error of the estimate (Syx%)** must be less than **10%**, in compliance with forestry engineering standards.
- The equations suggested for ZF2 meet these criteria and are considered highly reliable.

10. BIOMASS AND CARBON ALLOMETRY: COFFEE TREE

Biomass and carbon allometry in coffee trees is used for the accurate measurement of carbon stocks in agroforestry systems and commercial plantations. The destructive method is the most widely used for adjusting allometric equations and serves as the foundation for developing models that enable reliable biomass and carbon estimates at different growth stages of the plants.

10.1. Destructive Method: Basis for Allometric Equations

The direct method consists of felling and weighing coffee trees at fixed-area sampling points, followed by extrapolation to a per-unit-area basis. Coffee plants are cut at ground level, leaving a stump of approximately 10 cm in height. The plant parts are separated into specific compartments (trunk, thick branches, thin branches, leaves, flowers, fruits, coarse roots, and fine roots) and weighed individually.

For belowground biomass, trenches are dug around the trees, with excavation carried out at a distance of 20-30 cm from the plant. The roots are carefully washed to remove soil and then weighed. Samples from each compartment are oven-dried at 65°C until reaching a constant weight to determine dry biomass. **Figure 2** illustrates the complete process.

Figure 2. Fieldwork Images of the Destructive Method for Determining Total Weight Above and Below Ground in a Coffee Tree.

The plant mass was compartmentalized into:

I. Trunk;
II. Large branches (basal diameter ≥ 10 cm);
III. Small branches (basal diameter < 10 cm);
IV. Large roots (basal diameter > 2 cm);
V. Small roots (basal diameter ≤ 2 cm);
VI. Leaves;
VII. Flowers and fruits.

All dendrometric variables, except for canopy diameter, were measured after uprooting the trees. Height and diameter variables were obtained using a measuring tape. The variables were collected as follows:

I. **Canopy height:** Total plant height minus stem height, representing the length of the canopy;

II. **Total height (*ht*):** Distance from the tree base to its top;

III. **Commercial height (*hc*):** The portion of the stem with commercial value, i.e., the usable part of the trunk;

IV. **Canopy diameters:** Two diameters were measured (north-south and east-west directions);

V. **Number of nodes:** Manual count of all nodes.

10.2. Allometric Equations for the Monte Carmelo - MG Region

Based on the collected data, a single-entry allometric equation was developed, using only the independent variable **DAB** (Diameter at the Base, measured at up to 10.0 cm from the ground). The equation developed for the study area, based on **DAB**, resulted in a determination coefficient (**r²**) of 85% and a standard error of estimate (**Syx**) of 13%.

NIn the **absence of a site-specific equation**, **Tero Carbon recommends** the equation by **Rezende (2023)**, developed for Fazenda Santa Bárbara, Monte Carmelo - MG, for 4- and 6-year-old coffee trees:

$$Btot = 2,276 \times DAB^{0,765}$$

where:

Btot = Total crop biomass (Kg);

DAB = Diameter at the base, measured at up to 10.0 cm from the ground (cm).

10.3. Biomass to Carbon Conversion

To determine the amount of stored carbon and carbon equivalent in coffee trees, conversion factors developed for plantations in the Monte Carmelo region, Minas Gerais, at two different ages, can be used (**Table 4**).

Table 4: Water and Carbon Content in 4- and 6-Year-Old Coffee Trees at Fazenda Santa Bárbara, Monte Carmelo, Minas Gerais, Brazil.

AGE (YEARS)	WATER CONTENT (%)	CARBON CONTENT (%)
4	59.13	42.79
6	55.07	44.73

The equation for estimating total carbon (**Ctot**) is:

$$Ctot = Btot \times TC$$

where:

$Ctot$ = Total carbon (Kg);

TC = Specific carbon content by age.

10.4. Notes for Developers

- Projects may present site-specific biomass equations adjusted using local data, following Measurement, Reporting, and Verification (MRV) guidelines.
- The use of independent variables such as Circumference at Breast Height (CBH) and total height is recommended for greater accuracy.
- The choice of variables should balance cost-benefit in data collection and its impact on model precision.

10.5. Final Considerations

Applying **specific allometric models** for coffee cultivation allows for **more precise estimates** of biomass and carbon stocks. Whenever possible, the use of **locally adjusted equations** is recommended to **increase accuracy** and **reduce uncertainties** in carbon estimates.

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VERSION HISTORY

VERSION	DATE	NOTES
1.0	04/01/2025	Initial version approved by the Management and released for public consultation.