



PEMSEA Regional Methodology for Blue Carbon Project Accounting

A Harmonized Guide for Estimating Carbon Stocks, Sequestration, and GHG Reductions in Coastal Ecosystems

Annex A

Mangrove Ecosystems – Carbon Stock and Sequestration Assessment Methods



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About Us

Partnerships in Environmental Management for the Seas of East Asia (PEMSEA) is a regional coordinating mechanism for the sustainable coastal and marine development in the East Asian Seas Region.

PEMSEA Resource Facility

P.O. Box 2502, Quezon City 1165, Philippines

Tel: (+632) 8929-2992 Fax: (+632) 8926-9712

Email: info@pemsea.org

www.pemsea.org



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Table of Contents

A.1	Introduction.....	5
A.2	Carbon Pools in Mangrove	6
A.3	Project Design and Sampling Framework.....	8
A3.1	Defining Project Area Boundaries.....	9
A3.2	Project Area Stratification.....	10
A3.3	Sampling Design.....	12
A3.4	Plot Layouts by Carbon Pool	13
A3.5	Number of Plots and Precision Targets.....	14
A3.6	Monitoring Schedule and Operational Considerations	15
A.4	Data Collection and Analysis Methods for each Carbon Pool	15
A4.1	Aboveground Biomass (AGB).....	16
A4.2	Belowground Biomass (BGB)	28
A4.3	Soil Organic Carbon (SOC).....	34
A4.4	Deadwood.....	50
A4.5	Litter	55
A.5	Carbon Stock Estimation for Mangrove Project Area.....	57
A5.1	Compute Total Carbon Stock per Plot (Mg/ha)	57
A5.2	Aggregate Carbon Stock to Stratum Level	58
A5.3	Compute Total Carbon Stock for the Project Area	58
A5.4	Uncertainty in Carbon Stock Estimation.....	59
A.6	Carbon Sink (Sequestration Rate) Estimation in Mangrove Ecosystems	61
A6.1	Stock-Difference Method for Mangroves.....	62
A6.2	Gain–Loss Method for Mangroves	64
A.7	Measurement of Direct Carbon Emissions (CO₂ FLUX)	70
A7.1	Measurement Approaches	71
A.8	Uncertainty and QA/QC	75

A8.1	Sources of Uncertainty	75
A8.2	Reporting uncertainty in stocks and sinks	76
A8.3	Recommended QA/QC Procedures.....	76
A.9	Methodological Levels for Mangrove Carbon Accounting	77
A9.1	Field Data Collection and Laboratory Methods by Measurement Category	78
A9.2	Methodological Levels for Carbon Accounting Estimates	80
A.10	Monitoring.....	82
A10.1	Monitoring Plan.....	83
A10.2	Monitoring Schedule	83
A10.3	Parameters and Data Collection.....	84
A10.4	Tools and Methods.....	87
A10.5	Quality Assurance / Quality Control (QA/QC) and Uncertainty Assessment	87
A10.6	Reporting templates.....	87
A.11	Regional Parameter Tables	95
A11.1	Mangrove Species in the East and Southeast Asia Region.....	95
A11.2	Allometric Equations	96
A11.3	Root-to-Shoot Ratios.....	97
A.12	Templates and Examples	98
A12.1	Sample Uncertainty Computations	98
REFERENCES		102

A.1 Introduction

Mangrove Ecosystems

Mangrove forests are intertidal ecosystems distributed along tropical and subtropical coastlines, particularly in estuaries, deltas, lagoons, and sheltered bays. Dominated by salt-tolerant (halophytic), predominantly woody plant species, mangroves are ecologically significant and play a major role as carbon sinks.

Mangroves thrive in environments characterized by fluctuating salinity, tidal inundation, and anoxic sediments. To persist in such dynamic conditions, mangrove species exhibit a suite of structural, physiological, and reproductive adaptations. These include pneumatophores and stilt roots for gas exchange in waterlogged soils; mechanisms for salt exclusion, secretion, or storage; viviparous or cryptoviviparous reproduction to enhance seedling survival; and waxy leaves with specialized stomatal control to regulate transpiration under saline stress. These adaptations enable mangroves to form dense, structurally complex forests that stabilize coastlines, trap sediments, and store organic carbon.

Ecosystem Functions and Services

Mangroves provide a wide range of ecosystem services, commonly grouped into provisioning, regulating, supporting, and cultural categories. Provisioning services support coastal livelihoods through fisheries, fuelwood collection, and other forest products. Regulating services include shoreline protection, erosion control, and climate regulation through carbon sequestration. Supporting services encompass nutrient cycling, soil formation, and critical habitat provision for numerous marine and terrestrial species. Cultural services include recreation, tourism, education, and scientific research opportunities.

The capacity of mangroves to provide these services is strongly influenced by their structural and ecological complexity. Species composition and spatial zonation along tidal gradients, vertical canopy stratification, and the density of stems and aerial root structures (such as pneumatophores and prop roots) all shape how mangroves interact with their environment. These features regulate hydrodynamic processes, enhance sediment deposition, and facilitate organic matter accumulation. Forest structure types—such as fringe, riverine, and basin mangroves—vary in productivity, species diversity, and carbon storage capacity, reflecting differences in geomorphic setting and hydrological regime.

Mangroves and Their Role in Carbon Storage and Sequestration

Mangroves are among the most carbon-rich ecosystems globally, owing to their ability to store large volumes of organic carbon in both living biomass and deep, waterlogged soils. Aboveground, their dense wood and extensive canopy support high biomass accumulation. Belowground, the regular deposition of organic matter, coupled with anaerobic soil conditions, slows decomposition and facilitates long-term carbon preservation in sediments—often for centuries to millennia.

Understanding and quantifying mangrove carbon is critical for climate mitigation and blue carbon strategies. Assessments of both carbon stock (the total stored carbon at a given time) and carbon sink potential (the rate of carbon accumulation) inform national greenhouse gas inventories, support nature-based climate solutions, and underpin carbon crediting mechanisms. Accurate measurement requires standardized, ecosystem-appropriate methods that capture the heterogeneity in above- and below-ground biomass and soil carbon across different mangrove forest types and site conditions. These assessments are essential to ensure transparency, comparability, and scientific credibility in carbon accounting frameworks.

A.2 Carbon Pools in Mangrove

Mangrove ecosystems store carbon across multiple interconnected pools, both above and below ground. These carbon reservoirs vary in magnitude and persistence, reflecting the ecosystem's structural complexity and the dynamic interactions between vegetation, sediments, and hydrological processes. Collectively, these pools contribute to the exceptional carbon sequestration capacity of mangroves and are the focus of carbon stock and flux assessments.

Carbon stored in mangroves originates from two principal sources: **autochthonous** and **allochthonous** inputs. *Autochthonous carbon* is produced within the mangrove system itself—primarily through photosynthesis by mangrove vegetation—and is stored in the form of living biomass, litter, and root-derived organic matter in the soil. In contrast, *allochthonous carbon* is transported from external sources, such as terrestrial catchments, upland forests, or offshore waters, and deposited into mangrove sediments by tidal flows and fluvial processes. Both types of carbon contribute to the soil carbon pool, while aboveground and belowground biomass is mainly autochthonous.

Aboveground Biomass (AGB)

Aboveground biomass includes the trunks, branches, leaves, and other aerial components of living trees. This pool typically accounts for 10% to 21% of total carbon stocks in mangroves.

Belowground Biomass (BGB)

Belowground biomass comprises coarse and fine roots and can contribute approximately 5% to 15% of the total carbon stock. Root structures not only stabilize coastal soils but also promote long-term carbon storage by delivering organic matter to oxygen-poor environments where decomposition is limited.

Soil Organic Carbon (SOC)

Soil carbon is consistently the dominant carbon pool, typically representing 50% to over 90% of the total ecosystem carbon in mangroves. Mangrove soils—often anaerobic and saturated—are highly effective at preserving organic matter over long periods. SOC includes both autochthonous carbon from root inputs and decomposed litter, as well as allochthonous carbon from transported organic material.

Deadwood and Litter

This pool includes non-living organic material such as standing dead trees, downed woody debris, and leaf litter. Dead biomass typically contributes 2.5% to 5% of the total carbon stock, though its magnitude can increase in disturbed or early successional stands. While leaf litter is usually consumed rapidly or exported by tides, large woody debris can persist and eventually contribute to the soil carbon pool. Inputs to this pool may be either autochthonous (originating from the mangrove stand) or allochthonous (transported debris).

Inorganic Carbon

In addition to organic carbon, inorganic carbon may be present in mangrove soils, particularly in carbonate-rich or marine-influenced environments. This pool consists primarily of calcium carbonate (CaCO_3) from biogenic sources such as shells and coral fragments. Although inorganic carbon is not included in blue carbon accounting due to its geochemical origin and lack of contribution to atmospheric CO_2 removal, it must be identified and corrected for during laboratory analysis to avoid overestimation of SOC. Inorganic carbon is typically removed using acid pre-treatment prior to elemental analysis.

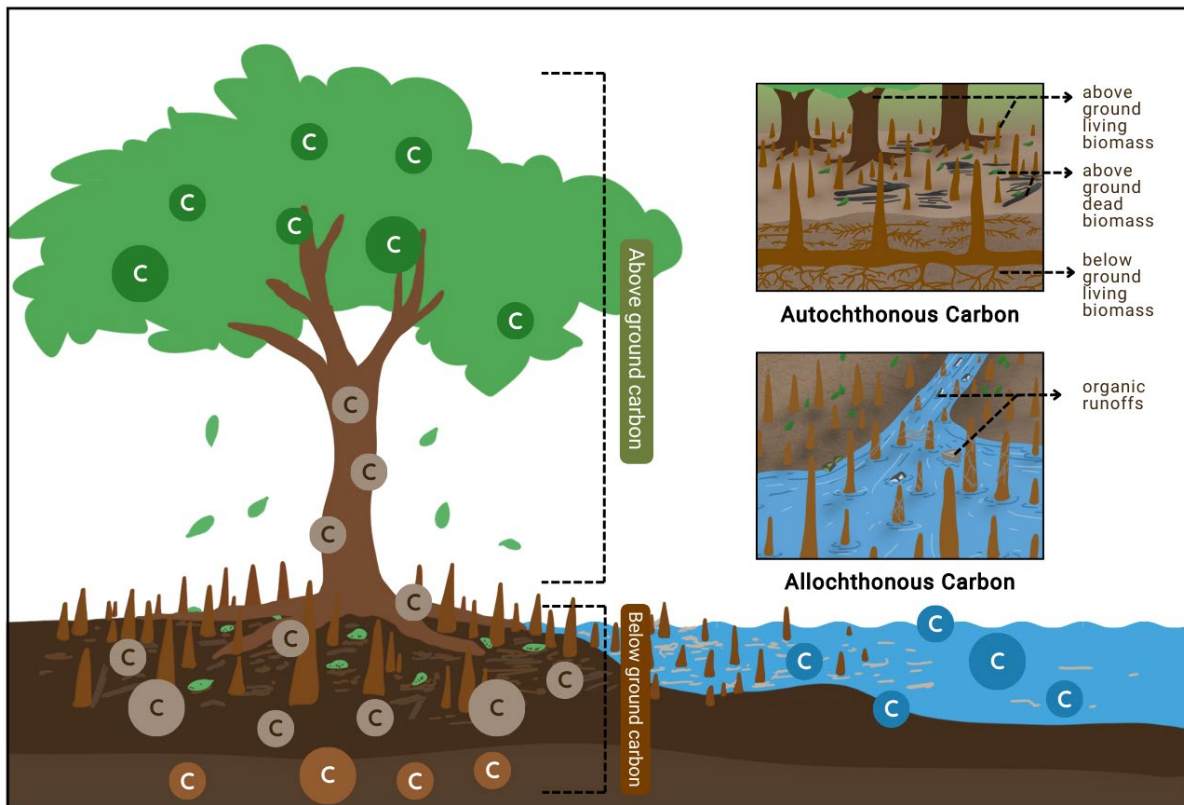


Figure 1: Carbon Pools in Mangroves

The accurate assessment of carbon stocks in mangrove ecosystems requires methods tailored to each pool—biomass measurements for vegetation and dead wood, coring and lab analysis for soils, and corrections for the presence of inorganic materials. These assessments must also consider the origin of stored carbon, particularly in soil, where the distinction between autochthonous and allochthonous carbon can influence carbon accounting protocols.

A.3 Project Design and Sampling Framework

Designing a robust blue carbon assessment in mangrove ecosystems requires a methodical approach that ensures spatial accuracy, ecological representativeness, and measurement efficiency. The core components of project planning include spatial boundary delineation, stratification into ecologically distinct units, and deployment of well-distributed sampling plots. These steps form the foundation for accurate carbon stock and sequestration estimates and ensure that project outputs are credible for use in climate mitigation, carbon crediting, or national reporting.

A3.1 Defining Project Area Boundaries

The geographic boundaries of a mangrove carbon assessment project form the foundation for stratification, plot selection, monitoring design, and spatial extrapolation of carbon estimates. Proper delineation also ensures consistency in temporal and spatial reporting.

A3.1.1 Project Boundary Determination

The spatial extent of the project area should align with the project's scope and objectives—ranging from localized restoration sites (tens of hectares) to landscape- or jurisdiction-wide assessments (up to hundreds of thousands of hectares). Boundaries must cover the full extent of relevant mangrove ecosystems, including key geomorphological zones and habitat types, while excluding ineligible or non-tidal areas. Once established, these boundaries should remain fixed throughout the monitoring period. If adjustments are unavoidable due to land use change, administrative reclassification, or technical correction, they must be documented and accounted for in stock and emission estimates.

A3.1.2 Tools and Data Sources for Delineation

Accurate mapping of the project area provides the foundation for all design and monitoring activities. The tools and datasets commonly used include:

- Remote Sensing and Mapping Products: High-resolution satellite imagery, drone-based orthomosaics, and aerial photographs provide visual identification of mangrove extents and structural patterns.
- Geographic Information Systems (GIS): GIS platforms support digitization of boundaries, integration of base layers (topography, land use, vegetation), and spatial analyses.
- GNSS/GPS/Beidou Devices: Used in the field to collect accurate boundary coordinates, typically with an error margin of less than 1 meter.
- Administrative and Thematic Maps: Local government data on land use, protected areas, and forest zoning help define legal or jurisdictional limits.
- Field Verification: On-site reconnaissance and visual inspection are critical for confirming boundaries, especially where image interpretation is ambiguous (e.g., mixed land cover, dense canopy).

A3.2 Project Area Stratification

Stratification divides the project area into distinct ecological sub-units—called strata—that are relatively homogeneous in terms of key characteristics influencing carbon stocks and fluxes. These characteristics include vegetation type, forest structure, soil conditions, hydrology, and land-use history. Stratification ensures that the variability across the landscape is systematically accounted for during sampling and monitoring.

By grouping similar areas together, stratification improves the efficiency and reliability of field sampling. It reduces the number of plots needed to meet statistical confidence targets, helps avoid oversampling areas with low variability, and ensures that high-variability zones are adequately represented. Stratification also supports transparent and repeatable project reporting by linking observed carbon values to well-defined landscape units.

A3.2.1 Stratification Criteria for Mangrove Ecosystems

Stratification should be guided by factors that are known to influence carbon pool size and behavior. In mangrove systems, the following criteria are commonly used:

1. Vegetation Structure and Composition

- Dominant species or genus (e.g., *Rhizophora*, *Avicennia*, *Sonneratia*).
- Forest type (e.g., tall mangrove, scrub/dwarf, *nypa*-dominated).
- Canopy cover or NDVI values (from satellite imagery).
- Plantation vs. natural mangrove stands, and planting age (for restoration projects).

2. Soil and Sediment Properties

- Organic matter content, sediment depth, and texture (clay, peat, mineral).
- Salinity and waterlogging, influencing methane emissions and decomposition.
- Presence of carbonate substrates (e.g., coral sands or shell fragments).

3. Hydrology and Geomorphology

- Tidal regime (e.g., regularly inundated vs. high-elevation areas).
- Proximity to rivers, estuaries, lagoons, or the open sea.
- Presence of impounded or hydrologically isolated areas (e.g., ditches, abandoned aquaculture).

4. Land Use and Management History

- Areas with past or ongoing conversion (e.g., rice paddies, aquaculture, degraded mangroves).
- Zones restored from former land uses (e.g., bare flats, reclaimed areas).

- Management regimes (protected vs. unprotected, active planting vs. natural regeneration).

A3.2.2 Common Mangrove Strata Types

Specific examples of strata used in mangrove ecosystems include:

- Oceanic fringe mangroves
- Estuarine riverine forests
- Basin mangroves (e.g., inland depressions)
- Dwarf or scrub mangrove zones
- Nypa palm zones (monospecific palm-dominated stands)
- Mixed or transitional zones between dominant types
- Disturbed or regenerating patches

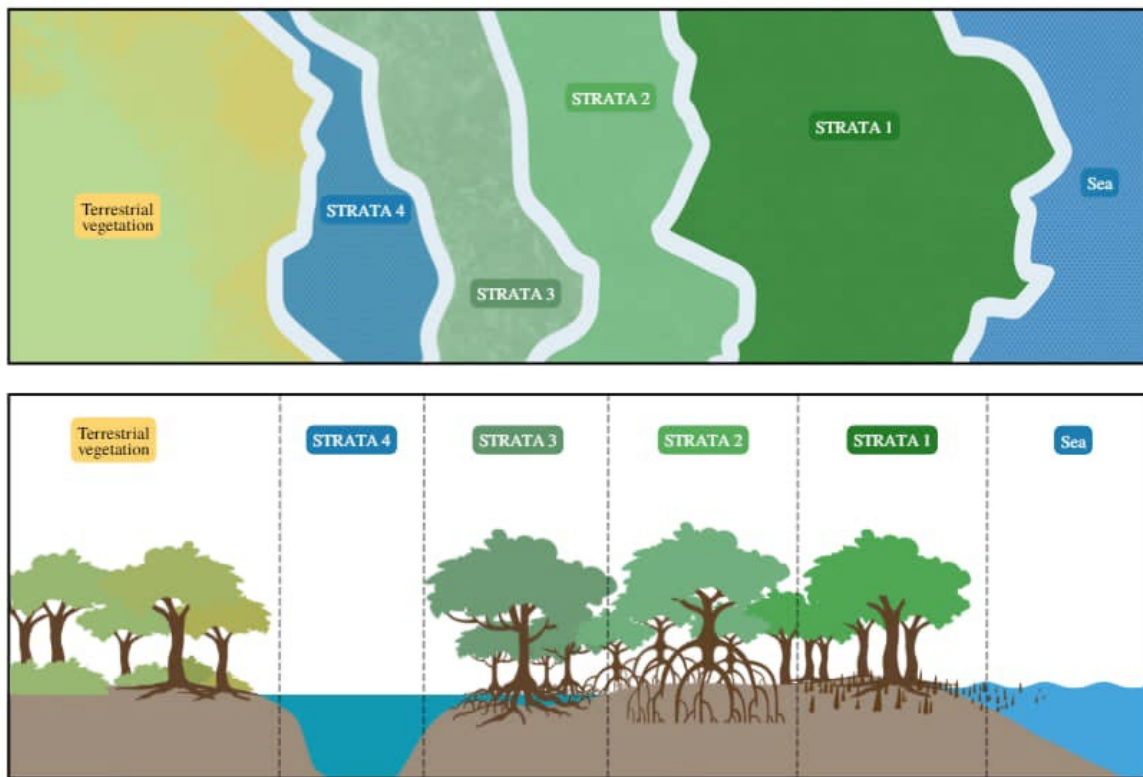


Figure 2: Sample Mangrove Stratification

A3.2.3 Tools and Methods for Defining Strata

Stratification should be informed by both field observations and spatial data. Key tools include:

- Remote sensing: Satellite imagery (e.g., Landsat, Sentinel), NDVI/NDMI indices.
- GIS layers: Elevation, land cover, soil type, hydrology.
- Drone surveys: For fine-scale mapping of canopy structure or disturbance.
- Local knowledge and field reconnaissance: Essential for interpreting image-based classifications.

Once strata have been defined, sampling design within each stratum must ensure that variability is well captured without introducing bias.

A3.3 Sampling Design

Plots within each stratum should be positioned without prior bias and designed to minimize trampling and disturbance. Accepted placement strategies include:

- **Linear Layouts:** Used where plots follow a natural gradient (e.g., from shore to upland) or when dense vegetation makes random access challenging.
- **Stratified Random Sampling:** Plots are randomly allocated within strata to capture variability.
- **Probability-Based Grid:** Hexagonal or square grids overlaid within strata, sampling one random point per grid cell to balance randomization and even coverage.

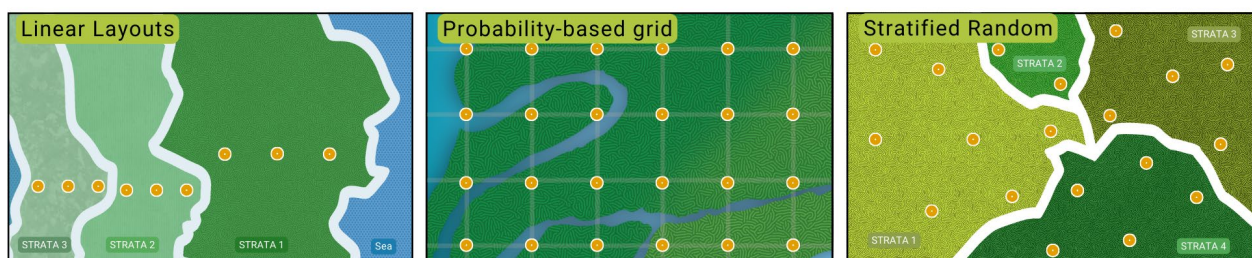


Figure 3: Sample Mangrove plot location design

A3.4 Plot Layouts by Carbon Pool

Different carbon pools within mangrove ecosystems require specific plot sizes and shapes to balance sampling efficiency, representativeness, and safety. To streamline fieldwork, nested plot designs—where smaller subplots for specific pools are placed within larger plots—are recommended. This allows simultaneous sampling of trees, shrubs, regeneration, litter, dead wood, and soils without duplicating effort.

A3.4.1 Aboveground Biomass (Trees and Shrubs)

For aboveground biomass of trees and shrubs, circular plots with a radius of seven meters (153.9 sqm) or square plots measuring 10 by 10 meters are commonly used. In very large or structurally complex forests, plots as large as 50 by 50 meters may be established to capture adequate representation of stand variability. For shrub-dominated areas or dwarf mangroves, smaller 5 by 5 meter square plots, or even 2 by 2 meter plots, are appropriate. Extremely dense dwarf mangroves, where individuals are small and numerous, may instead be assessed using half-circle plots with a radius of 2 meters (6.3 sqm). Where shrubs grow under tree-dominated canopies, 2 by 2 meter nested subplots within the larger tree plots are often established to capture the contribution of the understory.

A3.4.2 Regeneration, Herbs, Litter, and Pneumatophores

For regeneration, herbs, litter, and pneumatophores, smaller sampling units are used because of the small size and density of these components. Litter is typically assessed within microplots ranging from 30 × 30 cm to 1 m², commonly standardized at 0.5 × 0.5 m. Seedlings should be assessed using the dedicated seedling subplot procedure described in Section A4.1.3: 2-m-radius circular subplots for seedling counts, or 2 × 2 m square subplots in dense or very young stands. Pneumatophore density is counted in designated microplots placed within the main tree plots, ensuring consistent sampling across strata.

A3.4.3 Dead and Downed Wood

Standing dead trees are fully enumerated within the plot boundary for live trees. Large downed wood (fallen trunks/branches with diameter ≥ 10 cm and length ≥ 1 m) is also surveyed within the plot, using a consistent inclusion rule (e.g., midpoint inside). Fine woody debris (<10 cm) is sampled in four fixed-area microplots (e.g., 1 m² or 0.5 × 0.5 m) placed systematically from the plot center at the cardinal bearings on a fixed radius scaled to plot size.

A3.4.4 Soil Organic Carbon (SOC)

For soil organic carbon (SOC), coring is conducted near the center of each plot, with one to three cores typically taken per plot and a minimum of six cores per stratum to ensure statistical representativeness. Each core is usually five to ten centimeters in diameter, depending on the corer type, and is sampled at multiple depth intervals. Standard depth layers include 0 to 30 centimeters and 30 to 100 centimeters, with deeper layers sampled if organic deposits persist until bedrock, mineral layers, or coral sands. The choice of coring device is determined by the sediment conditions, such as grain size, saturation, and the presence of woody roots.

This nested, multi-pool approach ensures that all relevant carbon stocks—above- and belowground biomass, dead wood, litter, and soil carbon—are consistently and efficiently captured within each stratum of the mangrove project area.

A3.5 Number of Plots and Precision Targets

Determine sampling intensity from the variability within each stratum and the adopted precision target. For key carbon-pool estimates, the sampling target is a 95% confidence interval with a half-width no greater than 10% of the estimated mean. Assess sampling precision separately from other sources of uncertainty, including measurement and model uncertainty.

As a starting point, each stratum within the project area should contain at least three plots per carbon pool. These plots are established to capture the range of variability within each stratum, covering different vegetation structures, soil conditions, and tidal zones. While three is the minimum, the final number of plots often needs to be higher, especially in large or highly variable strata. Greater variability in biomass or soil carbon will require additional sampling to meet the precision target.

The number of plots required can be calculated using tools such as Winrock's sample size calculators (available for download at https://winrock.org/wp-content/uploads/2016/03/Winrock_SamplePlot_Calculator_2014_0.xlsx), which use key inputs such as the area of the stratum, the standard deviation of preliminary data (or literature values), and the desired confidence level. These tools help determine the sample size needed to minimize error without overextending field resources.

Allow for inaccessible plots, damaged markers and unusable samples when planning sample size. Document the allowance for anticipated sample losses. After initial measurements, reassess variability and increase sampling where necessary to meet the adopted precision target.

A3.6 Monitoring Schedule and Operational Considerations

For long-term monitoring of mangrove carbon stocks, permanent plots—with tagged trees and clearly marked boundaries—are preferred, as they allow repeated measurements to track changes over time with high consistency. Temporary plots may be used in situations where only a one-time assessment is needed or where permanent markers are likely to be lost, such as in areas prone to erosion, storms, or heavy disturbance.

Conduct mangrove measurements under comparable, site-appropriate seasonal and tidal conditions across monitoring periods. Record measurement dates, tidal conditions, relevant environmental observations and disturbances. Set monitoring intervals by carbon pool and monitoring objective in accordance with Section A10.2.

Fieldwork in mangrove ecosystems is inherently tied to tidal cycles, which restrict accessibility. Most surveys must be conducted during low tide, when plots are exposed and traversable. Typically, sampling windows last around four hours, following the “Rule of Twelfths” for tidal scheduling. In higher-elevation zones, where inundation is less frequent, the sampling window may be extended.

Proper documentation is essential for every monitoring event. Teams must record complete plot metadata, including precise coordinates, administrative location, dominant species, planting patterns, timing, and any disturbances or notable site conditions. Establishing permanent photo points—four photos taken in the cardinal directions from the plot center—is strongly recommended to visually track site changes alongside quantitative measurements.

A.4 Data Collection and Analysis Methods for each Carbon Pool

Data collection and analysis in mangrove ecosystems must be adapted to the characteristics of each carbon pool. Aboveground biomass, belowground biomass, soil organic carbon, deadwood, and litter each require specific equipment, sampling techniques, and analytical procedures, while some methods and instruments are shared across pools.

A4.1 Aboveground Biomass (AGB)

Aboveground biomass carbon accounting includes all living plant material above the substrate within the plot and typically represents a major carbon pool. To ensure that all above-ground growth is accounted for, standardized measurements of trees and woody stems are taken with specialized instruments and converted to biomass using allometric equations rather than destructive harvesting. Individual estimates are summed to the plot and reported as carbon stock using the adopted carbon fraction.

A4.1.1 Field Equipment for Biomass and Vegetation Measurements

Tree Diameter and Stem Measurements

- Phi band, DBH tape, or tree girder
- Vernier or digital calipers (for small stems or dwarf mangroves)
- Measuring tape (for stem circumference or height baselines)

Tree Height and Canopy Measurements

- Height gauge, clinometer, or laser range finder
- Tower ruler or telescoping measuring pole
- Densiometer (for canopy cover estimates)

Plot Establishment and Navigation

- Measuring tape (for delineating plots and transects)
- GPS unit, GNSS, or Beidou Navigation Satellite System (for precise geolocation)
- Compass and work maps (for field orientation)
- **Stakes or permanent markers (for fixed plot monitoring)**

Weighing and Sample Handling (Field)

- Portable field scales ($\pm 0.5\%$ accuracy)
- Sample bags, labels, waterproof markers, and tally sheets
- Icebox or coolers (to preserve fresh biomass)



Figure 4: Tools for aboveground biomass data collection

A4.1.2 Measurement of Trees and Saplings

In mangrove assessments, trees are typically defined as woody plants with a DBH ≥ 10 cm, while saplings are smaller woody plants with DBH < 10 cm but ≥ 2 cm. For each tree and sapling within the plot, measure the following:

- Species – for selecting the correct allometric equation.
- Diameter at Breast Height (DBH) – measured at 1.3 m above ground.
- Tree Height – measured for large trees if required by the biomass equation
- Location or ID Tag – to ensure trees can be re-measured in permanent plots.

Optional measurements (for some plot types or structural studies): crown dimensions (diameter, depth), canopy cover, crown area/volume (especially for scrub or dwarf mangroves).

How to Collect Data:

1. Species Identification

Begin by identifying the species of each tree. Rely on local field guides or expert verification to confirm species in the field. If identification is uncertain, photograph key characteristics—such as bark texture, root structure, leaf shape, and any reproductive parts like flowers or fruits—for post-field identification.

2. Tree Tagging and Point of Measurement (POM) Marking

For permanent plots, locate and tag each tree. Assign a unique number to every tree within the plot and clearly mark the POM at 1.3 meters above the ground, or at the adjusted height for irregular trees, using durable paint or a tree tag. This ensures that future surveys can replicate measurements at the exact same location.

3. Diameter Measurement

Measure the DBH. Use a diameter tape for precision or a tree caliper for rapid surveys. Take the measurement along the trunk axis at 1.3 meters.

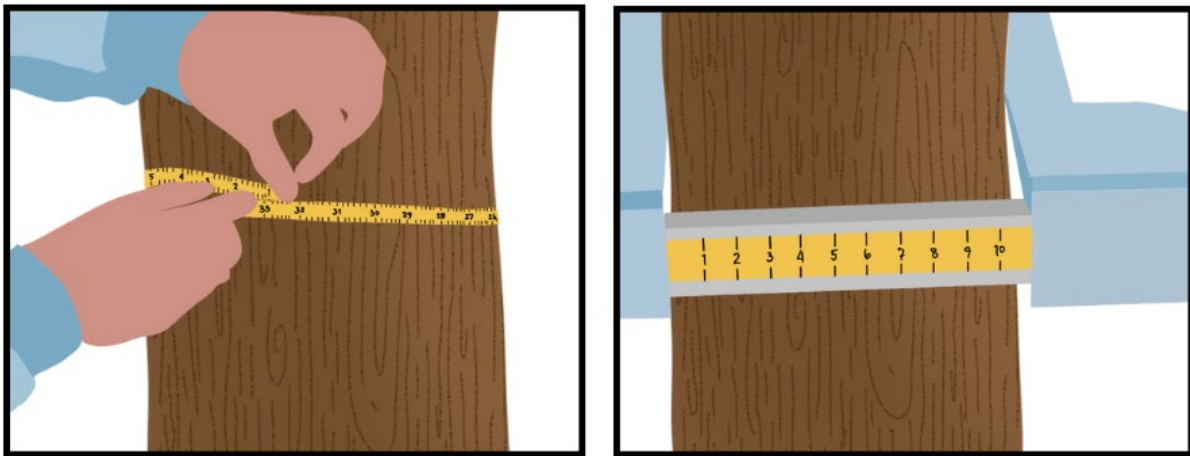


Figure 5: Ways to measure diameter at breast height: using tape (DBH = Circumference/ π) and using caliper



Figure 6: Measuring for DBH in the field

For irregular trees—such as buttressed, sloping, or stilt-rooted individuals—follow the adjustment rules provided (Figure 7), and make sure any deviations are clearly noted on the field sheet for transparency.

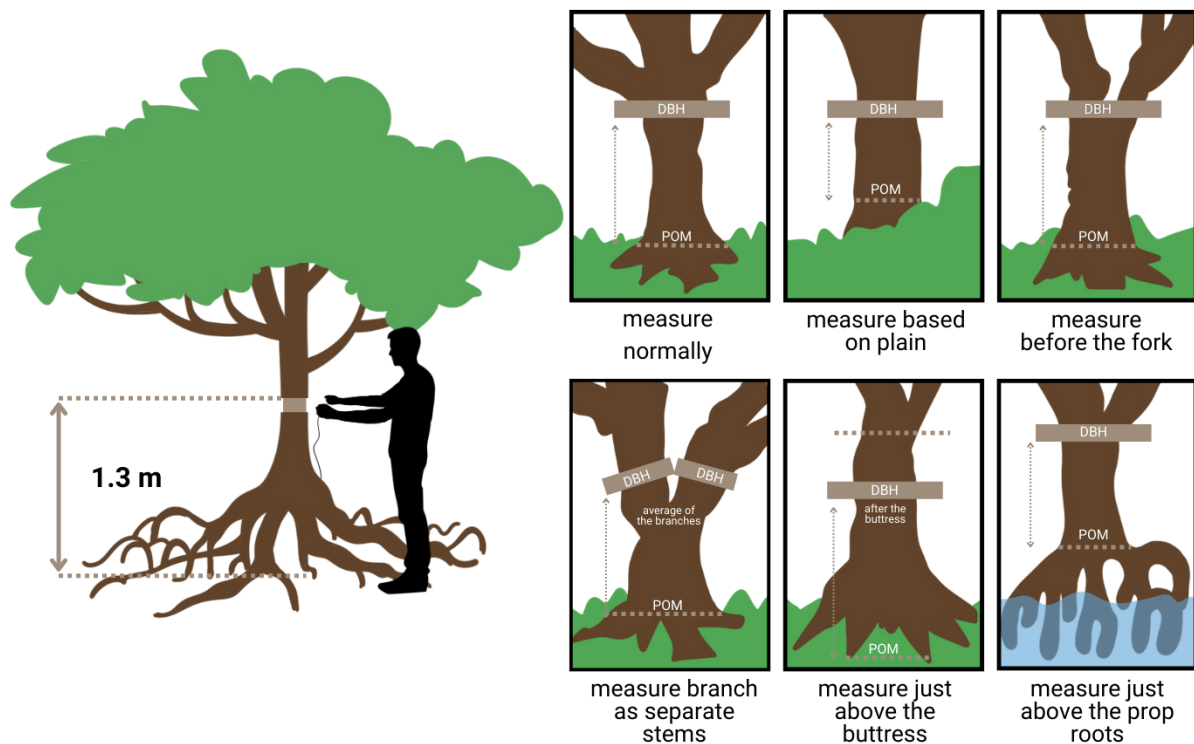


Figure 7: Measuring for diameter at breast height for irregular mangrove trees

4. Tree Height Measurement

If required by the selected biomass equation or if the data will support remote sensing validation or canopy structure studies, measure the total tree height. For small or medium-sized trees, a simple measuring pole is sufficient. For taller individuals, use a clinometer or a laser rangefinder to ensure accuracy.

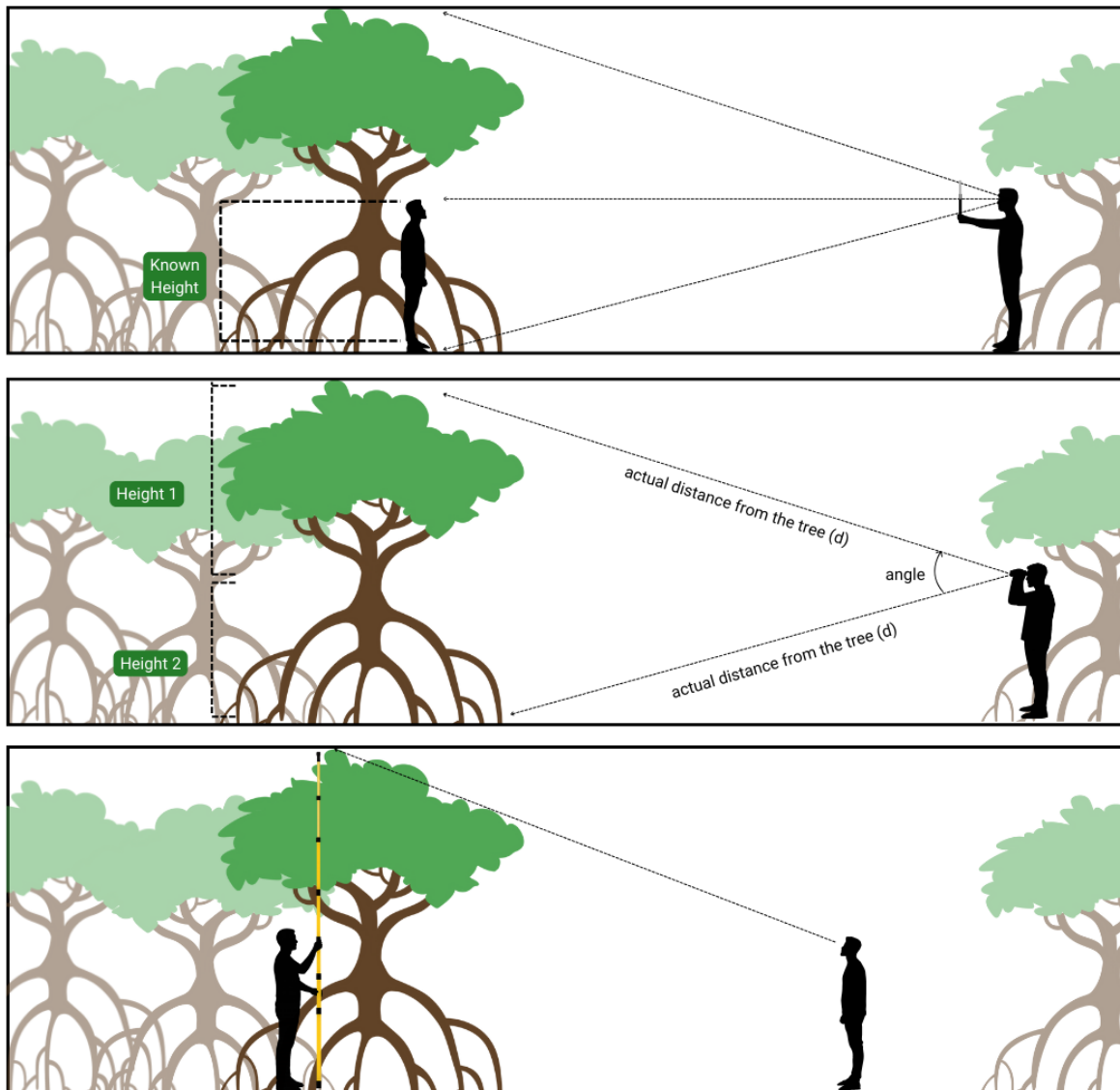


Figure 8: Three field methods to estimate tree height. (A) Visual estimation: hold a short vertical stick at a known reference height on the trunk (e.g., 1.5 m) and visually count how many “stick-heights” reach the treetop to estimate total height. (B) Rangefinder/clinometer method: stand a known distance from the stem, aim at the treetop and the base, and read the height from the

instrument's display, (C) Height-pole method: extend a telescopic pole to the crown contact point and read height directly (stack or segment poles if height exceeds one pole).

5. Canopy and Crown Structure (optional)

When needed, record additional canopy structure data. Use a spherical densiometer to measure canopy cover, taking readings in the four cardinal directions from the plot center or subplot center. For scrub or dwarf mangroves, where canopy dimensions strongly influence biomass estimates, measure the crown's widest width (W1), the width perpendicular to W1 (W2), and crown depth. These measurements can then be used to calculate crown area and volume, which serve as inputs to specialized allometric models.

A4.1.3 Measurement of Seedlings

In mangrove ecosystems, seedlings are defined as woody plants between 10 and 30 centimeters in height and under 2 centimeters in diameter. Unlike litter or non-tree vegetation, which can often be excluded, seedlings contribute significantly to stand regeneration and overall carbon stocks, especially in dynamic or recently restored stands.

How to Collect Data:

1. Subplot Establishment

Inside each main tree plot, set up 2-meter radius circular subplots for seedling counts. In dense or very young stands, use 2×2 meter square subplots instead. These subplots are typically nested within the larger circular or square plots used for tree and sapling measurements so that all vegetation layers are monitored efficiently.

2. Seedling Identification and Count

Within each subplot, count all live seedlings and record their species (if identifiable). Use field guides or expert verification for identification. When identification is uncertain, take photographs of distinctive features (roots, bark, leaves, flowers, fruits) for post-field verification.

3. Biomass Estimation Methods

There are two acceptable methods for determining seedling biomass and carbon contribution:

- Without Sampling (Using Published Factors):
If reliable species-specific or generic biomass/carbon conversion factors are available, multiply seedling density by published average dry biomass values. This

method is recommended when preservation of seedlings for future monitoring is a priority.

- **With Destructive Sampling (For Higher Accuracy or No Published Data):**
When no applicable factors are available, or when higher accuracy is required, conduct destructive sampling on a representative sample of seedlings collected from outside the permanent monitoring plots to avoid disrupting tagged individuals. Ensure the sample reflects the observed size range.

4. Field Harvesting and Wet Weight Measurement

Clip all aboveground parts (leaves, stems, branches) at the soil surface using scissors or clippers. Place samples in labeled plastic or paper bags. At the field site, weigh and record the total wet weight of the harvested seedlings using a portable balance.

5. Subsampling and Laboratory Drying

Take a representative subsample (approximately 300 grams) from the pooled wet sample. Dry this subsample in a laboratory oven at 70–105°C (or at 60°C for sensitive tissues) until a constant weight is achieved. Record the dry weight to determine the dry-to-wet ratio.

The field measurements collected—particularly DBH, tree height, species identity, and seedling counts—serve as the foundational inputs for biomass estimation methods. Depending on the data available and the level of accuracy desired, different estimation approaches may be applied, ranging from allometric equations to biomass expansion factors or destructive sampling.

A4.1.4 Estimating aboveground biomass using Allometric Equations

Allometric equations are mathematical models that relate tree dimensions, such as diameter at breast height (DBH) and height (H), to the biomass of a tree. These equations are commonly used in mangrove biomass estimation because direct measurement of tree biomass (e.g., by harvesting and weighing) is often impractical and destructive.

Allometric equations vary in complexity and accuracy, depending on the input variables.

General Allometric Equations Using DBH and Wood Density

A commonly used form of general allometric equations relates DBH to biomass, incorporating wood density (ρ) as a key variable to account for species differences. These equations are suitable for estimating AGB when only basic tree measurements are available.

General form of equation:

$$AGB = a \times (DBH)^b \times \rho^c \quad \text{Equation 1}$$

Where:

- AGB = Aboveground biomass (kg)
- DBH = Diameter at breast height (cm)
- ρ = Wood density (g/cm³) (note that 1 g/cm³ = 1 Mg/m³)
- a, b, and c = Coefficients that vary based on the specific allometric model or study

Including wood density adjusts for interspecies differences, making these equations broadly applicable across mangrove species where no species-specific models exist.

Species-Specific Allometric Equations Using DBH

For greater accuracy in estimating AGB, species-specific allometric equations may be used, which are tailored to individual species or groups of species. These equations often rely on DBH alone, without wood density, but they are based on detailed data collected from the species in question.

General form of equation:

$$AGB = a \times (DBH)^b \quad \text{Equation 2}$$

Where:

- AGB = Aboveground biomass (kg)
- DBH = Diameter at breast height (cm)
- a and b = Coefficients calibrated to the species or genus

Species-specific equations are developed through extensive sampling and are considered more reliable than general equations, particularly when assessing biomass for specific species in a localized area.

General Allometric Equations Using DBH, Height, and Wood Density

In some cases, both DBH and tree height are used in combination with wood density to provide a more accurate estimate of biomass. This approach is particularly useful in forests with high structural complexity, where height significantly influences biomass.

General form of equation:

$$AGB = a \times (DBH^b) \times (H^c) \times \rho^d \quad \text{Equation 3}$$

Where:

- AGB = Aboveground biomass (in kg)
- DBH = Diameter at breast height (in cm)
- H = Height of the tree (in meters)
- ρ = Wood density (in g/cm³) (note that 1 g/cm³ = 1 Mg/m³)
- a, b, c, and d = Coefficients specific to the allometric model or study

Species-Specific Allometric Equations Using DBH and Height

When both DBH and height are available, species-specific equations may provide a more accurate estimation of biomass. These equations are based on data collected from specific species and take into account the tree's height in addition to its diameter.

General form of equation:

$$AGB = a \times (DBH)^b \times (H)^c \quad \text{Equation 4}$$

Where:

- AGB = Aboveground biomass (in kg)
- DBH = Diameter at breast height (in cm)
- H = Height of the tree (in meters)
- a, b, and c = Coefficients specific to the species or forest type

Applying Allometric Equations to Plot Data

Once field measurements of DBH, height, and species identification are collected, the next step is to select the most appropriate allometric equation for each species or group. Species-specific equations should be prioritized when available and valid for the study region, while general equations can be used when species-specific models are lacking. If wood density values are required but not measured, they may be sourced from published databases for the species or genus.

For each tree in the plot, the selected equation is applied individually using its measured DBH (and height and wood density, if required). The resulting biomass estimates (in kilograms) are then summed across all trees within the plot to derive the total aboveground biomass for that plot. This sum is typically standardized by dividing by the plot area (to express biomass in Mg/ha), making the results comparable across plots and strata.

A4.1.5 Estimating aboveground biomass using Biomass Expansion Factors

Biomass Expansion Factors (BEFs) provide a practical alternative to allometric equations by converting measured tree volume into biomass estimates. BEFs are especially useful when tree volume measurements (bole volume, VOB) are available from forest inventories or remote sensing, but species-specific allometric equations are either unavailable or impractical to apply. This approach is effective for mangrove biomass estimation, particularly for large-scale assessments or projects relying on existing volume data.

BEFs allow a straightforward conversion from the volume of the tree bole (VOB) to total aboveground biomass, including branches and leaves, based on the assumption that biomass increases proportionally with volume.

General form of equations using Biomass Expansion Factors

$$AGB = BEF \times VOB \times \rho \times 1000 \quad \text{Equation 5}$$

Where:

- AGB = Aboveground biomass (kg)
- BEF = Biomass Expansion Factor (dimensionless)
- VOB = Volume of bole (m³)
- ρ = Wood density (g/cm³) (note that 1 g/cm³ = 1 Mg/m³)

BEFs vary by forest type, species, and site conditions and can be influenced by forest age, growing conditions, and climate. Site-specific BEFs are preferred, as they reflect local forest structure, but IPCC default BEFs can be used when local data is not available. If developing site-specific BEFs, field measurements of additional components (e.g., branches and foliage) may be needed.

Applying Biomass Expansion Factors (BEFs) to Plot Data

Field-collected measurements of DBH, height, and species are first used to calculate the bole volume (VOB) for each tree using standard forestry volume equations, which incorporate trunk form factors to account for tapering. Once VOB is calculated, the BEF method converts this volume to total aboveground biomass by multiplying by a suitable BEF and the species-specific or default wood density (ρ).

The aboveground biomass for each tree is then summed across all trees within the plot. Finally, the total biomass is standardized by dividing by the plot area to express the results in megagrams per hectare (Mg/ha).

A4.1.6 Destructive Sampling Methods (Weight-to-Biomass Estimation)

For samples that have been harvested, labeled, and oven-dried to a constant weight, the next step is to convert their measured dry weight into aboveground biomass (AGB). This method, while labor-intensive, provides the most direct and accurate estimate of biomass because it is based on the actual plant material rather than modeled relationships.

For each harvested seedling, the aboveground components—stems, leaves, and any branches—are weighed individually after drying. These component weights are then summed to obtain the total dry mass for each plant:

$$\text{AGB} = \text{Weight of Trunk} + \text{Weight of Branches} + \text{Weight of Leaves} \quad \text{Equation 6}$$

The dry weight per seedling can then be scaled up by multiplying by the density of seedlings recorded in the nested subplot to estimate the total biomass contribution from seedlings per plot. If sub-sampling was done (e.g., 300 g subsamples dried and scaled back to total wet mass), the calculated dry-to-wet weight ratio is used to adjust all field weights before applying this formula.

Once the total biomass for seedlings is estimated, it is standardized by dividing by the plot area to express the result as megagrams per hectare (Mg/ha).

A4.1.7 Total AGB Carbon for the plot

The total AGB for the plot is calculated by summing the aboveground biomass of all individual trees within the plot:

- a. Compute AGB for Each Tree:

For each tree, estimate the AGB using the selected method (e.g., allometric equations, biomass expansion factors, or destructive sampling). For instance:

$$AGB_{tree} (kg) = f(DBH, height, wood density)$$

where f is the allometric equation specific to the species or site.

- b. Sum AGB for All Trees in the Plot:

Add the AGB values for all trees within the plot:

$$AGB_{plot}(Mg) = \frac{\sum AGB_{tree}(kg)}{1000} \quad \text{Equation 7}$$

This gives the total aboveground biomass for the entire plot (in Mg).

- c. Standardize to Megagrams per Hectare (Mg/ha)

The total AGB for the plot is standardized to Mg/ha by dividing by the plot area (in hectares):

$$AGB(Mg/ha) = \frac{AGB_{plot}}{PlotArea(ha)} \quad \text{Equation 8}$$

- d. Convert AGB to Carbon Stock:

To estimate the carbon stock in AGB, multiply the total biomass by the carbon fraction (CF), typically 0.47 for mangroves:

$$C_{AGB}(Mg C/ha) = AGB(Mg/ha) \times CF \quad \text{Equation 9}$$

A4.2 Belowground Biomass (BGB)

Belowground biomass comprises the live root system of mangrove trees, including pneumatophores where present. Quantification typically relies on AGB measurements (e.g., DBH, height) applied through BGB allometric equations or root-to-shoot ratios, minimizing destructive excavation. Targeted root or pneumatophore sampling may be used for site-specific calibration when published factors are lacking; plot-level estimates are aggregated and converted to carbon using the adopted carbon fraction. Where site-specific calibration is pursued, small-diameter root cores and limited pneumatophore harvests outside permanent plots are recommended to avoid disturbing monitoring plots.

A4.2.1 Field Equipment for Belowground Biomass Measurements

Use general plot and handling tools as described for AGB. Additional specialized instruments for accessing and processing root material include:

Root Extraction and Sampling

- Soil augers and corers (for retrieving root samples at depth)
- Shovels or spades (for coarse root excavation near the surface)
- Monolith boxes or sampling cylinders (for intact fine root collections)
- Graduated core liners (with known inner diameter), rubber stoppers, ruler/caliper for segment thickness

Root Cleaning and Handling

- Sieves or mesh screens (for separating roots from soil)
- Buckets and water supply or portable washing stations (for fine root cleaning)
- Sample bags, labels, and field balances (for weighing and transport)
- Aluminum foil or paper envelopes for oven-drying; waterproof markers; field tally sheets

A4.2.2 Belowground Vegetation Measurement

Belowground vegetation measurements follow the AGB tree inventory and, where present, include microplots for pneumatophore counts or sampling.

How to Collect Data:

1. Species Identification and Tree Tagging

Begin by identifying all mangrove species within each main tree plot using field guides or expert verification. Photograph distinctive features such as roots, bark, leaves, and reproductive structures if identification cannot be confirmed in the field. For permanent

monitoring, tag each tree and mark the point of measurement for DBH at 1.3 meters above the ground or above prop roots, following the DBH measurement protocols in Section A4.1

2. Diameter Measurement and Data Recording

Measure the DBH for all tagged trees using a DBH tape or tree caliper. Record the species, DBH, and tree ID for every individual. For irregular cases such as buttressed or prop-rooted trees, follow the adjusted DBH measurement rules described in Section A4.1 and document any deviations clearly in the field sheets. These DBH values will serve as the primary inputs for estimating belowground tree biomass through allometric equations during data analysis.

3. Pneumatophore Density and Structure Assessment

Establish dedicated microplots for assessing pneumatophore density within or immediately adjacent to the main tree plots. Use a standard size of 50 × 50 centimeters (0.25 m²), adjusting to 30 × 30 centimeters or up to 1 × 1 meter depending on stand density. Count all pneumatophores within each microplot, recording their species and height where possible. These measurements will later be used to estimate biomass, either through conversion factors or site-specific relationships.

4. Destructive Sampling (If required)

When destructive sampling is necessary—for instance, when published biomass factors are not available—collect pneumatophores or small individuals outside the permanent plots to avoid disturbing ongoing monitoring. For pneumatophores, cut individuals cleanly at the base using shears and place the material in labeled bags. If needed, record wet weight in the field and group samples by species and height class (e.g., 5-cm classes). These samples will undergo the same cleaning, drying, and weighing steps described below for root material.

5. Root Coring (Optional, for Site-Specific Calibration)

Belowground biomass may also be measured directly using small-diameter root cores to obtain site-specific calibration data. Insert a corer (5–8 cm internal diameter) vertically into the substrate to capture the main root zone (typically 0–30 cm or up to 50 cm in mature stands). Carefully extract the core and transfer the material to a tray or mesh bag. Gently wash sediment through a 0.5–1 mm sieve until only coarse (>2

mm) and fine (<2 mm) roots remain. Place all cleaned root material into labeled bags or envelopes for transport to the laboratory.

6. Sample Processing (Pneumatophores and Roots)

In the laboratory, rinse remaining sediment from pneumatophore and root samples using clean water. Remove non-root debris (wood fragments, leaves, bark pieces) and, where feasible, separate roots into coarse and fine fractions or sort pneumatophores by height class for more detailed reporting. Transfer all cleaned material into pre-labeled envelopes or paper bags and oven-dry at 60–70 °C to constant mass (typically 48–72 hours). After drying, cool samples in a desiccator to prevent moisture uptake and weigh them using an analytical balance (±0.01 g). Record dry weights by species, size class, or depth interval as applicable, and enter results into standardized data sheets for subsequent biomass and carbon stock calculations.

A4.2.3 Estimating belowground biomass using Allometric Equations

Two alternative methodological pathways are available for estimating belowground biomass: (1) tree-based estimation using allometric equations or root-to-shoot ratios; or (2) sample-based estimation using root cores or pneumatophore harvests. These approaches should be used independently and not combined to avoid double-counting.

Allometric equations for BGB estimation in mangroves are typically based on easily measurable parameters like DBH, and in some cases, tree height and wood density. These equations are species-specific or generalized for mangroves and provide an indirect way to estimate the root biomass without the need for destructive sampling.

General BGB Allometric Equations Using DBH and Wood Density

General allometric equations incorporate both DBH and wood density (ρ) to estimate BGB. These equations are useful when species-specific data are not available and can provide reliable estimates for various mangrove species.

General form of equation:

$$BGB = a \times (DBH)^b \times \rho^c \quad \text{Equation 10}$$

Where:

- BGB = Belowground biomass (kg)
- DBH = Diameter at breast height (cm)
- ρ = Wood density (g/cm³) (note that 1 g/cm³ = 1 Mg/m³)
- a, b, and c = Coefficients specific to the species and model

Species-specific BGB allometric equations using DBH only:

Species-specific equations tend to be more accurate and are developed for particular mangrove species. These equations typically rely on DBH as the sole input.

General form of equation:

$$BGB = a \times (DBH)^b \quad \text{Equation 11}$$

Where:

- BGB = Belowground biomass (kg)
- DBH = Diameter at breast height (cm)
- a and b = Species-specific coefficients

Species-specific BGB allometric equations that make use of DBH and Height

When height data is available, these equations provide more accurate estimates by incorporating both DBH and tree height (H).

General form of equation:

$$BGB = a \times (DBH)^b \times H^c \quad \text{Equation 12}$$

Where:

- BGB = Belowground biomass (kg)
- DBH = Diameter at breast height (cm)
- H = Total tree height (m)
- a, b, and c = Species-specific coefficients

A4.2.4 Biomass estimation using Root to Shoot Ratio

An alternative method for estimating BGB is the root-to-shoot ratio, which relates the biomass of the roots (BGB) to the aboveground biomass (AGB). This ratio provides a simplified way to estimate BGB based on AGB calculations.

General form of equation:

$$BGB = AGB \times \text{Root to Shoot Ratio} \quad \text{Equation 13}$$

The Root-to-Shoot Ratio varies by species, ecosystem type, and environmental conditions. This method is often used when field-based BGB measurements are unavailable, but AGB data has been collected, allowing for a relatively quick estimation of belowground carbon.

A4.2.5 Biomass Estimation Using Collected Belowground Samples

If the project adopts sample-based estimation, belowground biomass is calculated directly from harvested material rather than from tree measurements.

Belowground biomass per unit area is estimated from the dry mass of recovered belowground material—either (a) roots collected from soil cores or (b) pneumatophores collected from defined microplots—divided by the sampled area.

For root cores:

$$BGB_{core}(Mg/ha) = \frac{\text{dry mass of roots (g)}}{\text{Area of core (cm}^2\text{)}} \times 100 \quad \text{Equation 14}$$

Where:

$$\text{Area of core (cm}^2\text{)} = \pi \times \left(\frac{\text{diameter}}{2}\right)^2 \quad \text{Equation 15}$$

For pneumatophore samples collected in small plots (e.g., 30×30 cm or 50×50 cm):

$$PNM_{plot}(Mg/ha) = \frac{\text{dry mass of pneumatophores (g)}}{\text{Area of plot (cm}^2\text{)}} \times 100 \quad \text{Equation 16}$$

Where:

$$\text{Area of plot (cm}^2\text{)} = \text{length (cm)} \times \text{width (cm)} \quad \text{Equation 17}$$

These sample-derived biomass values already represent per-hectare belowground biomass and may be used directly as the BGB pool when the project selects the sample-based method. In this case, the allometric/root-to-shoot ratio pathway is not applied for the plot. Sample-

derived BGB values may be added directly to the other carbon pools during total ecosystem carbon stock estimation.

A4.2.6 Total BGB Carbon for the plot (Allometric or Root-to-Shoot Ratio approach)

The following calculations apply only when the allometric or root-to-shoot method is used. They are not required when using the sample-based method, which already produces BGB in Mg/ha.

Apply the appropriate allometric equation (general or species-specific) to estimate the BGB of each tree. Use the root-to-shoot ratio specific to the tree species or general ratios when species-specific ratios are not available.

a. Total BGB per Plot:

After estimating the BGB for individual trees using either allometric equations or root-to-shoot ratio methods, sum the BGB values for all trees within the plot:

$$BGB_{plot}(Mg) = \frac{\sum BGB_{tree}(kg)}{1000} \quad \text{Equation 18}$$

This gives the total belowground biomass for the entire plot (in Mg).

b. Convert to Biomass per Hectare:

Standardize the BGB to per-hectare units by dividing the total BGB per plot by the plot area in hectares:

$$BGB (Mg/ha) = \frac{BGB_{plot}}{PlotArea(ha)} \quad \text{Equation 19}$$

c. Convert to Carbon Stock:

Multiply the total BGB by the carbon fraction (typically 0.47) to estimate the carbon content stored in the belowground biomass:

$$C_{BGB} = BGB (Mg/ha) \times CF \quad \text{Equation 20}$$

A4.3 Soil Organic Carbon (SOC)

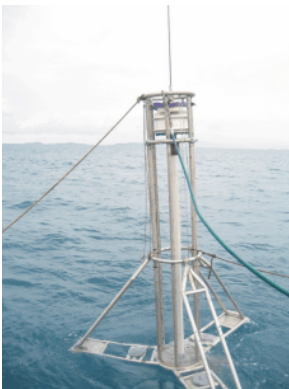
Soil organic carbon (SOC) accounts for the majority of carbon stored in mangrove ecosystems. Quantification relies on specialized field and laboratory methods: intact cores are collected with appropriate corers, and standardized analyses produce the key parameters—bulk density and organic carbon concentration—for each depth interval. Carbon stocks are then calculated per unit area by integrating these parameters to the specified depth.

A4.3.1 Field Equipment for Soil and Sediment Sampling and Analysis

The following tools and equipment are used to collect soil cores and measure sediment characteristics:

Coring and Soil Extraction Devices

- Ring soil sampler (for surface layers)
- Gouge augers and Russian peat corers (for organic/peat soils)
- Vibracores (for deep or sandy/muddy sediments)
- PVC tubes, rubber stoppers, syringes (for water-saturated samples)



Vibracorer



Russian peat corer



Piston corer



Eijkelkamp soil auger

Figure 9: Examples of sediment samplers

Depth and Elevation Measurements

- Soil depth probes or peat depth measuring devices (bamboo poles or avalanche probes)
- Rod Sediment Elevation Table (RSET) with marker horizons (to monitor vertical accretion and elevation change)
- Meter sticks or dive sticks (for shallow sediment or standing water depth)
-

Sample Handling Tools

- Sharp knives for subsampling
- Individual, labeled containers or plastic bags
- Icebox or cool box for preserving soil samples until laboratory processing



Figure 10: Tools for handling sediment samples and documentation

The following equipment are used for drying, homogenizing, and analyzing biomass and soil samples for carbon content:

Sample Preparation

- Drying ovens (60°C–85°C) for biomass and soil drying to constant weight
- Mortar and pestle or automated pulverizers (for homogenizing dried soil samples)
- Sieves for screening sediment samples
- Desiccators (for cooling samples to room temperature without moisture gain)

- Glass vials and thick glass bottles (for sample storage, with HgCl_2 fixative for water samples)

-

Carbon and Organic Matter Analysis

- CHN (carbon-hydrogen-nitrogen) elemental analyzer (for total carbon quantification via dry combustion)
- Muffle furnace (for Loss on Ignition, LOI, to estimate organic matter)
- Hydrochloric acid (HCl) for inorganic carbon removal in soils
- Microbalance and tin boats (for precise weighing of samples)



Figure 11: CHN Analyzer and Furnace

A4.3.2 Soil Sample Collection and Laboratory Analysis

To measure the soil carbon pool in mangroves, field teams must collect soil cores and derive three key parameters: soil depth, dry bulk density, and soil organic carbon content ($\%C_{org}$).

How to Collect Samples:

1. Soil Depth Determination

Before coring, determine the soil depth at several random points within each plot to assess vertical variability and identify the depth to refusal. Use a depth probe (e.g., bamboo rod, avalanche probe) or a soil corer to determine the maximum penetrable depth.

Advance the probe vertically until resistance is met (e.g., bedrock, coral sand, hardpan). Record this as the “depth to refusal.” Aim for a minimum sampling depth of 1 meter. Extend to 3–5 meters where deep organic horizons persist, as these can contribute substantially to long-term carbon storage.

2. Soil Core Collection

Once the site depth is characterized, collect soil cores using appropriate equipment for the substrate. In peat-rich or organic soils, use a Russian peat corer or Eijkelpkamp gouge auger, which can extend two to five meters and minimize compaction. For water-saturated, fine-grained soils, thin-walled PVC pipes can be driven vertically into the substrate, sealed with rubber stoppers, and retrieved. Begin by clearing away any surface litter or loose organic debris to avoid contamination of the core. Insert the corer vertically at a steady pace, avoiding excessive force that could compact the soil. If the corer meets an obstruction such as a root or coral fragment, withdraw it and select a nearby location rather than forcing the device, which could distort the sample. Once the corer reaches the desired depth, twist it gently to shear any fine roots and create a clean bottom surface, then seal the top to generate suction and prevent sample loss. Withdraw the core slowly, keeping it vertical to preserve layer integrity.

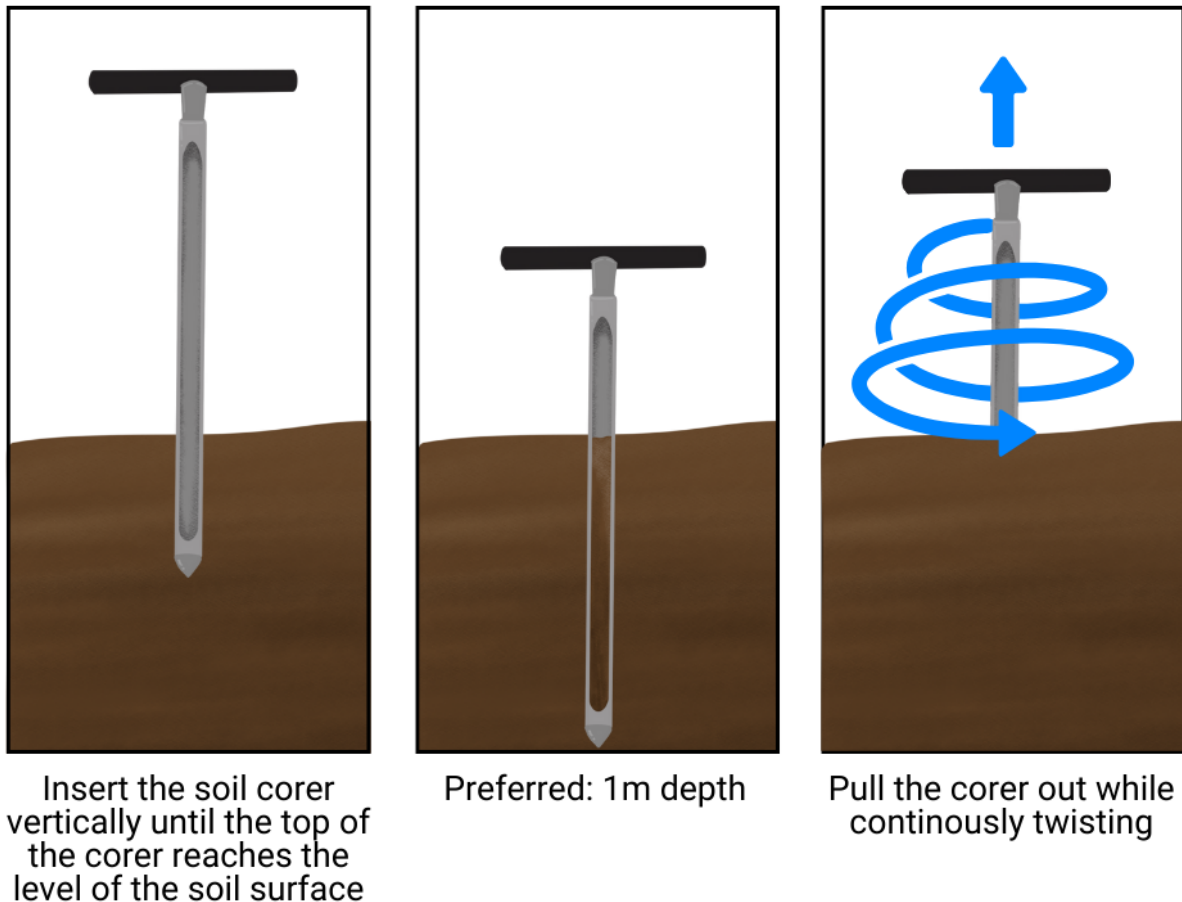


Figure 12: Soil Sampling with corer

3. Correction for Core Compression (Soil Compaction)

Core compression, or core shortening, can occur when coring devices are driven into saturated mangrove sediments, resulting in a recovered core that is shorter than the penetration depth. Because SOC calculations depend on accurate depth and volume measurements, compaction must be minimized and corrected when present.

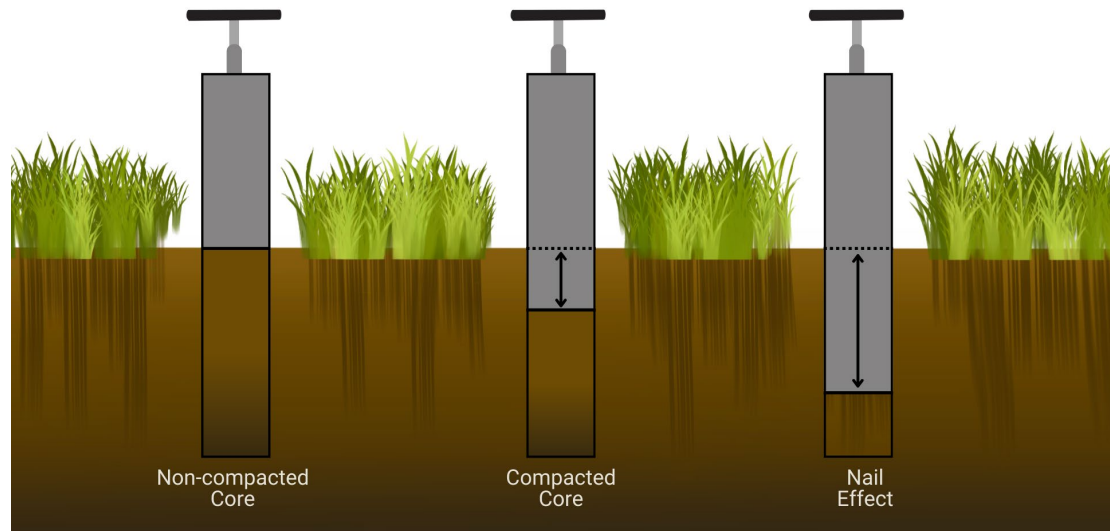


Figure 13: Core compression during coring, where recovered core length is shorter than penetration depth due to sediment compaction.

Minimizing compression: Use devices designed to preserve sediment structure (e.g., gouge augers, piston corers), insert them slowly, avoid obstructions such as thick roots or debris, and keep cores upright after extraction. Cores with severe compaction or obvious slumping should be rejected and re-collected.

Quantifying compression: When moderate compaction is unavoidable, a compaction correction factor (CCF) must be applied. It is calculated as:

$$CCF = \frac{L_{recovered}}{L_{inserted}} \quad \text{Equation 21}$$

where $L_{recovered}$ is the length of the extracted core and $L_{inserted}$ is the penetration depth.

To determine the in-situ thickness represented by an interval measured in the recovered core, divide the recovered interval thickness by the core compression factor:

$$L_{in\ situ, interval} = \frac{L_{recovered, interval}}{CCF} \quad \text{Equation 22}$$

Where:

$L_{in\ situ, interval}$ is the estimated original thickness of the sampled interval before compression (cm)

$L_{recovered, interval}$ is the thickness of that interval measured in the recovered core (cm)

For example, where $CCF = 0.86$, an 8.6-cm recovered interval represents an estimated 10-cm in-situ interval. Conversely, to sample an interval representing 10 cm in situ, select $10 \times 0.86 = 8.6$ cm of recovered material.

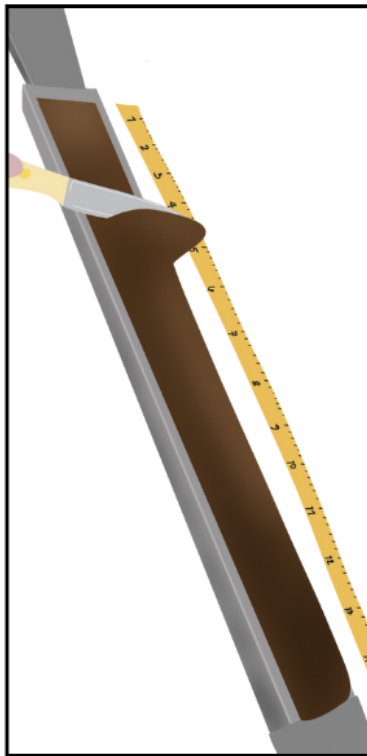
This correction assumes uniform compression along the core and shall be applied only where the shorter recovered length is attributable to compression rather than sediment loss. Document the assumption and use a consistent corrected interval-volume basis for bulk density and SOC calculations, so that compression is not corrected twice.

4. Field Observations and Documentation

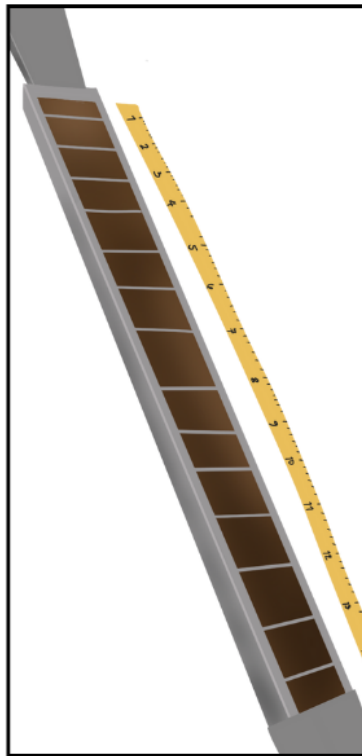
Record the characteristics of the core immediately after extraction. Note external traits such as soil color, texture, the presence of roots or coarse fragments, and any evidence of compaction during sampling. Photograph the full core against a measuring tape, including a visible label showing the core ID, depth, date, and site. Document the total recovered depth, the diameter of the corer, and any compression noted, as these factors affect bulk density calculations and may require the application of a compaction correction factor.

5. Subsampling and Sample Handling

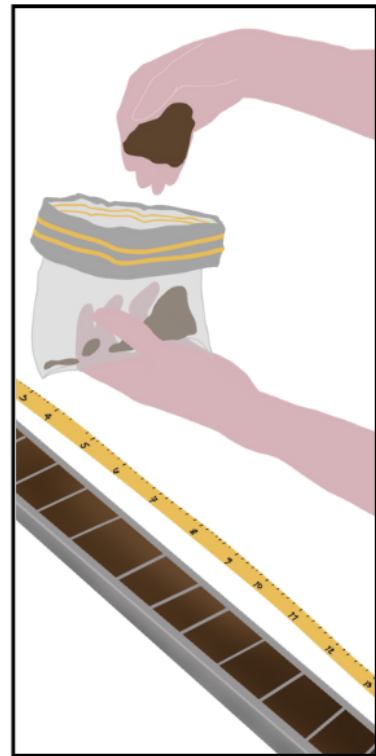
If the entire core is not transported intact to the laboratory, divide it into subsamples in the field. Segment the core by depth, typically using intervals such as 0–15 cm, 15–30 cm, 30–50 cm, 50–100 cm, and subsequent 50-centimeter sections for deeper deposits. For high-resolution studies, smaller increments (e.g., 2 cm from 0–10 cm and 5 cm thereafter) may be used. Always collect each subsample at the midpoint of the designated depth range. Retain the original sample volume by measuring core diameter and segment thickness, or by extracting a known volume with a calibrated syringe (1 cc = 1 cm³). Homogenize each subsample if mixing is necessary and place it in a labeled, airtight container, e.g. resealable plastic bags or plastic bottles.



"Flatten" soil samples
using a knife



Soil subsampling:
0-20 cm depth:
Every 2 cm
> 20 cm depth:
Every 4 cm



Collect subsamples
samples and place on
respective bags

Figure 14: Subsampling Soil



Figure 15: Sediment collection using auger in the field

6. Storage

Label every subsample with a durable, waterproof label that includes the core ID, depth range, site, plot number, date, coring device, and core diameter. Ensure that all labels are legible and securely affixed. Store samples immediately in coolers at approximately 4 °C, and transfer to a freezer or drying oven within 24 hours whenever possible. In remote locations where freezing or drying is not feasible, air-dry the samples and seal them in vacuum bags to slow microbial activity until laboratory processing.

7. Drying and Bulk Density Determination

Before determining sediment dry mass, remove identifiable living roots assigned to the belowground biomass pool. Retain dead root material according to the defined SOC pool boundary. Record removed material and retain the original sampled volume. Determine bulk density and organic carbon concentration on compatible sediment fractions so that living-root carbon is not counted again as SOC.

Dry samples at 60 °C until a constant weight is reached (typically 48–72 hours). Avoid temperatures above 105 °C, as high heat can oxidize organic matter and underestimate SOC. Once dry, cool samples in a desiccator for at least one hour and record dry weights. Calculate dry bulk density (DBD) by dividing the dry mass by the original sample volume:

$$DBD (g/cm^3) = \frac{\text{Dry soil mass (g)}}{\text{Volume sampled (cm}^3\text{)}} \quad \text{Equation 23}$$

Where the volume is calculated from the corer dimensions. For intact core segments, volume = $\pi \times \text{radius}^2 \times \text{segment thickness}$ (a full cylinder). If only half of the core was retained because the opposite side was scraped or lost, then volume = $(\pi \times \text{radius}^2 \times \text{segment thickness})/2$ (a half-cylinder).

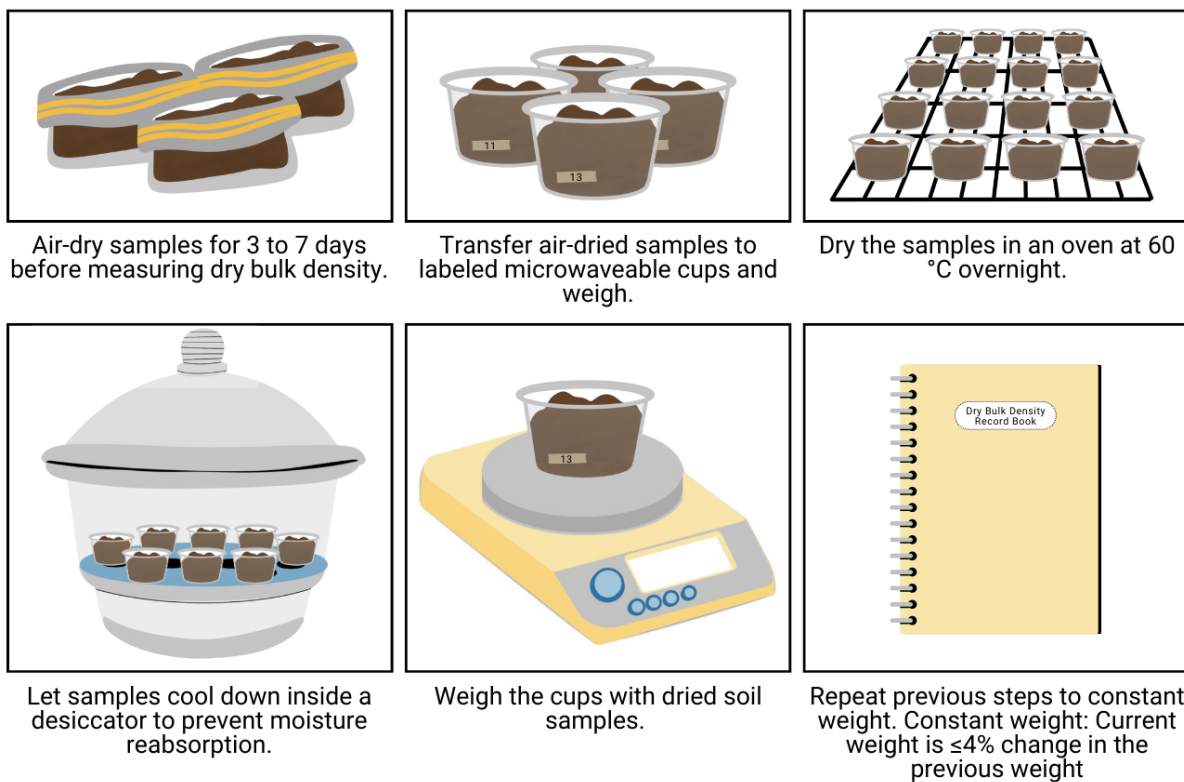


Figure 16: Steps for Drying Soil Samples to obtain constant weight

8. Testing for Carbonates

Before LOI analysis, take a small portion of the homogenized sample and apply a few drops of 1N HCl. Effervescence indicates the presence of inorganic carbon (carbonates), requiring acidification before combustion. If no effervescence occurs, the sample may proceed directly to LOI after drying.

9. Inorganic Carbon Removal by Gentle Acidification

When carbonates are present, inorganic carbon (IC) must be removed to avoid overestimating organic carbon during LOI. A slow acidification procedure is recommended to minimize loss of organic carbon.

Procedure:

a. Subsample preparation

Weigh approximately 5 g of dried, homogenized soil into a glass beaker or 50-mL conical tube.

- b. Initial acid test and treatment
Add enough 1N HCl to fully submerge the sample. Agitate gently (manual shaking or ultrasonic bath) for 15 minutes to break up clumps and allow uniform reaction.
- c. Overnight soaking and verification
Allow the sample to sit 18–24 hours until effervescence subsides. Add additional 1N HCl and repeat agitation. If no bubbles appear, carbonate removal is complete.
- d. Rinsing
Once soil settles (or after centrifugation), decant the acid (or remove the liquid with a pipette). Rinse with distilled water, allow settling or centrifuge again, and decant. Repeat three times.
- e. Drying
Dry the acid-treated sample at 60 °C overnight, cool in a desiccator, and reweigh. Determine organic carbon on an aliquot using a validated carbonate-correction or removal procedure. Express organic carbon relative to the original dry-sediment mass basis used in the stock calculation, documenting mass changes, recovery and applicable corrections. Determine bulk density on a separate untreated aliquot of known volume. Do not assume that acid-treatment mass loss consists entirely of carbonate or use that loss as a direct SOC measurement.

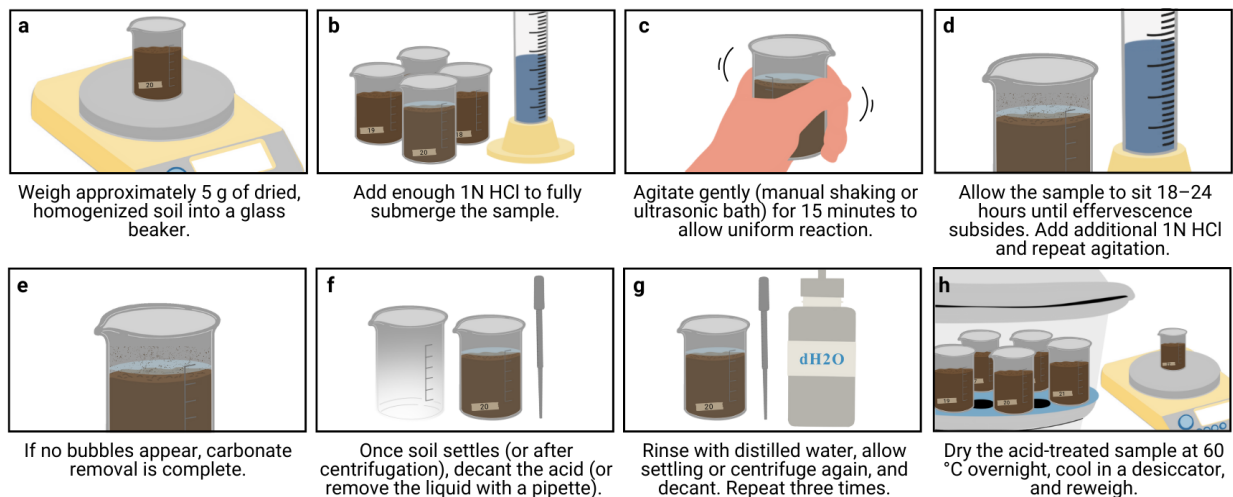


Figure 17: Acidification steps

After drying, the decalcified sample is ready for LOI combustion.

A4.3.3 Estimating Organic Carbon Content (%C_{org}) using Loss on Ignition

The Loss on Ignition (LOI) method is a widely used, low-cost technique to estimate soil organic carbon indirectly. LOI does not directly measure carbon; rather, it measures the organic matter content of the soil by determining the percentage of weight lost when combusted at high temperatures. Because organic matter contains other elements (hydrogen, oxygen, nitrogen, sulfur), the resulting %LOI must be converted to %C_{org} (the percentage of organic carbon) using a conversion factor or empirical relationship. This method may be applied directly to dried soil, or with acid pretreatment to remove inorganic carbonates in carbonate-rich sediments.

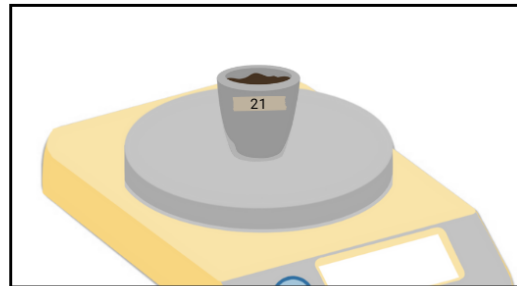
Process:

a. Sample Preparation:

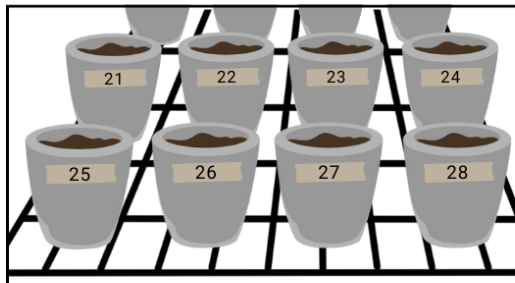
- For samples with carbonates, use the acid-treated and redried subsample.
- For samples without carbonates, homogenize and powder subsamples using a mortar and pestle.
- Weigh approximately 5 g of the dry sample for analysis.
- Oven-dry samples at 105 °C for 12 hours or overnight to remove residual moisture.
- Cool in a desiccator to prevent reabsorption of moisture.



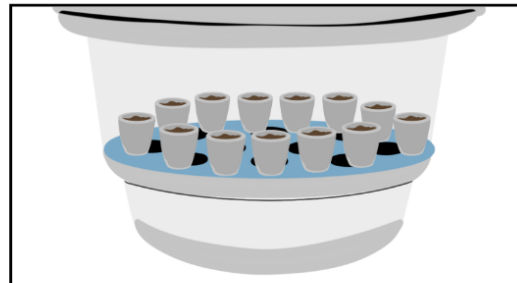
Powderize subsamples using mortar and pestle.



Weigh 5 grams of dried powdered subsamples.



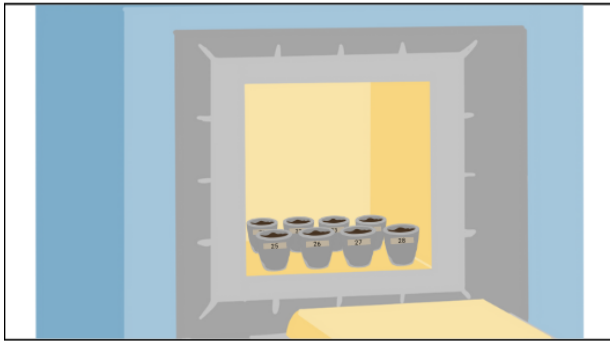
Oven dry at 105°C for 12 hours or overnight.



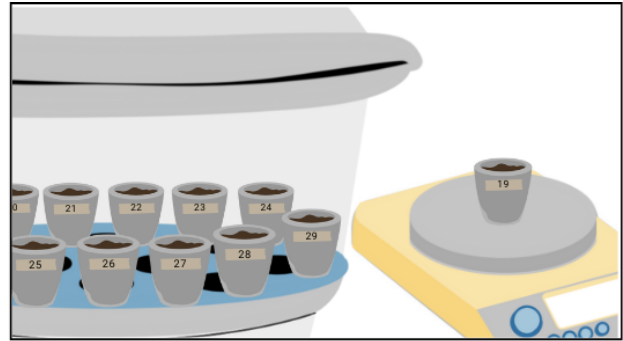
Dry crucibles with subsamples at 105°C for 12 hours, then let cool in a desiccator.

Figure 18: Sample preparation steps

- b. Weighing Before Ignition
 - Transfer the acid-treated, dried residue to a pre-weighed porcelain crucible.
 - Record the dry mass precisely using an analytical balance.
- c. Ignition
 - Place crucibles with dried (or acid-pretreated) samples in a muffle furnace at 450–550 °C for 4–8 hours.
 - Cool in a desiccator to room temperature.
 - Weigh crucibles with combusted samples.



Place the subsamples inside the furnace. Raise and stabilize the temperature at 450°C - 550°C for 4-8 hours.



Allow to cool down to room temp inside a desiccator then weigh.

Figure 19: Combusting samples

- d. Calculation
 - Calculate weight loss as %LOI

$$\%LOI = \frac{W_{pre} - W_{post}}{W_{pre}} \times 100 \quad \text{Equation 24}$$

Where

- W_{pre} = dry mass before ignition
- W_{post} = mass after ignition
- Convert %LOI to %C_{org} using a conversion factor (commonly 0.46–0.50 for mangrove and tidal soils, or site-specific empirical equations when available).

$$\%C_{org} = \%LOI \times CF \quad \text{Equation 25}$$

Where

- CF is the fraction of carbon in organic matter

LOI is particularly useful for large sample sets or when elemental analyzers are unavailable, but it can overestimate carbon due to structural water loss or inorganic carbon (e.g., carbonate shells). Where possible, calibrate the LOI-to-%C_{org} relationship by cross-validating with CHN analysis.

A4.3.4 Estimating Organic Carbon Content (%C_{org}) using Elemental Analysis

Elemental analysis (CHN analysis) is the most accurate method for directly quantifying organic carbon (%C_{org}) in soils. It involves combusting a dried, homogenized soil sample at high temperatures (around 1000 °C) and measuring the resulting gases (CO₂, H₂O, N₂) using gas chromatography or infrared spectroscopy. The carbon fraction is reported directly as %C_{org}.

Process:

a. Grinding and Homogenization

Pulverize dried samples to a uniform, fine powder using a mortar and pestle or mill, ensuring no cross-contamination between samples.

b. Combustion and Measurement

Place a measured subsample (often 2–200 mg, depending on carbon content) into the CHN analyzer, where it is flash-combusted in an induction furnace. The analyzer quantifies the gases released, reporting the carbon fraction as %C_{org}.

c. Correction for Inorganic Carbon (if needed)

Coastal soils often contain carbonates (e.g., shells, coral debris). These contribute inorganic carbon that will bias results. To isolate organic carbon:

- Acidification: Treat a subsample with hydrochloric acid (HCl) to volatilize carbonates as CO₂, then dry and reweigh.
- Ashing Method: Heat a separate subsample to 500 °C for ≥3 hours to combust organics, then analyze the residual ash for carbon. Subtract the inorganic fraction from total carbon.

Formula:

$$\%C_{org} = \text{Measured \%C from CHN (after inorganic C correction)}$$

Equation 26

CHN analysis avoids the assumptions inherent to LOI and yields precise carbon concentrations. These results, when combined with dry bulk density and depth interval data, allow calculation of soil organic carbon density and total SOC stocks across sampled areas.

A4.3.5 Total SOC for the plot

- a. For each soil layer within the core, SOC content is calculated as:

$$SOC_{layer} (Mg\ C/ha) = Depth\ (cm) \times Bulk\ Density\ (g/cm^3) \times \frac{\%C_{org}}{100} \times 100$$

Equation 27

The factor 100 converts from g C/cm² to Mg C/ha.

- b. Sum SOC Across All Depth Layers

$$SOC_{plot} = \sum SOC_{layer}$$

Equation 28

- c. SOC Reporting Depth

SOC stocks are normally reported for the upper 1 m of soil. Where sampling extends beyond 1 m, calculate and report the standardized stock using only the measured intervals within 0–100 cm; deeper stocks may be reported separately. Where sampling reaches less than 1 m, report the stock for the actual sampled depth and state that depth explicitly. Do not extrapolate a shallower measured stock to 1 m using a simple depth ratio. Comparisons between monitoring periods shall use a consistent depth basis.

A4.3.6 Sediment Accretion Monitoring Using RSET and Marker Horizon

Sediment accretion represents the rate at which new soil layers build up in mangrove ecosystems, providing the basis for estimating the Carbon Accumulation Rate (CAR). Tracking accretion over time is essential for carbon sink accounting. This requires combining sedimentation rate, soil dry bulk density, and organic carbon content (%C_{org}).

Accretion is measured using the Rod Surface Elevation Table (RSET) together with a Marker Horizon (MH). The RSET, a portable mechanical leveling device, is mounted on a permanent benchmark pole driven deep into stable strata (typically 8 m or more) so it remains fixed for many years. The Marker Horizon is a ~1 cm layer of inert material, such as feldspar or clean

sand, spread on the soil surface within a marked quadrat adjacent to the benchmark. These installations form permanent monitoring stations that are revisited repeatedly, often seasonally or annually, to track both soil surface elevation changes (from RSET) and vertical sediment deposition (from MH).

Deployment and Monitoring

1. Site Selection and Setup

Choose monitoring sites that represent the range of conditions within the mangrove area (e.g., seaward fringe, mid-zone, and landward forest). Mark GPS coordinates and establish durable markers so stations can be easily relocated for long-term monitoring.

2. Benchmark Pole and RSET Installation

Drive a stainless-steel benchmark pole deep into stable strata (often 8 m or more) until refusal, ensuring it will not move over time. Leave the top exposed above the surface. The RSET's portable leveling arm is mounted on this pole during each visit to serve as a stable platform for elevation measurements. The arm is equipped with nine pins, which are lowered to the soil surface and measured to determine the elevation relative to the benchmark.

3. Marker Horizon Application

Near the benchmark, lay out a small quadrat (commonly 0.25 m²) and spread an inert marker layer ~1 cm thick across the soil surface. Materials like feldspar powder, clean sand, or brick dust are commonly used, as they are visually distinct and chemically stable. Mark the quadrat boundaries for relocation.

4. Initial Baseline Measurement (T1)

Attach the RSET arm to the benchmark and record the initial elevation by lowering each pin until it gently touches the surface and measuring the height remaining above the arm. The marker horizon depth is considered zero at installation.

5. Repeat Monitoring (T2, T3, etc.)

Return to the site seasonally or annually (at consistent times of year) to repeat RSET measurements. At each visit:

- Repeat the RSET elevation measurements to detect changes in soil surface elevation relative to the benchmark.
- Extract sediment cores down to the marker horizon using a small coring device or gouge auger (5–10 cm diameter). Carefully section the core to measure the thickness of sediment accumulated above the marker, ensuring layers are not compacted or mixed. These samples can also be analyzed for bulk density and carbon content to quantify the carbon associated with the accreted material.

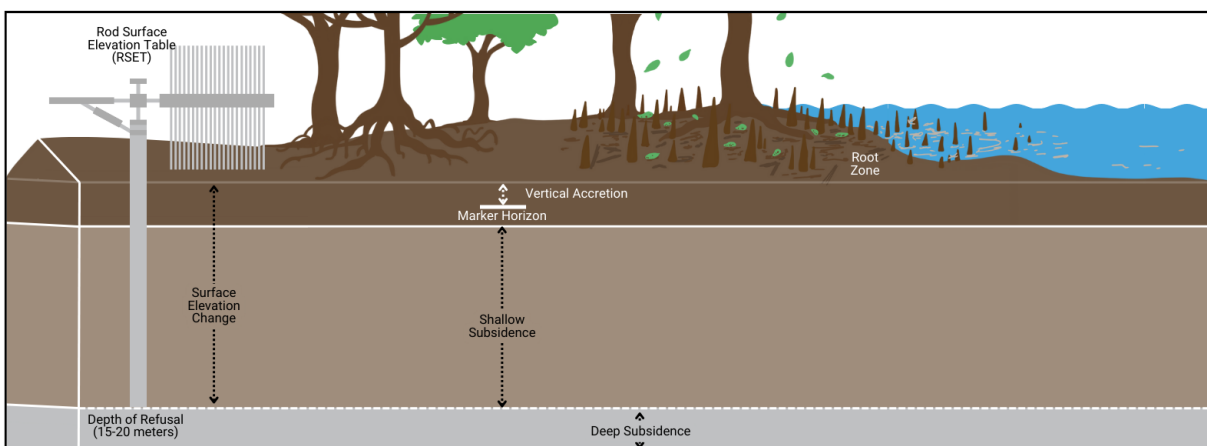


Figure 20: Sample RSET and elevation marker set up (Modified from Bomer et al. (2019))

A4.3.7 Isotope Sampling for Burial Rates

Isotope dating, typically using Lead-210 (^{210}Pb), is a key method for quantifying long-term sediment carbon burial rates in mangrove ecosystems. Unlike the Rod Surface Elevation Table and Marker Horizon method, which measures elevation change and vertical accretion over interannual scales, isotope dating can capture historical accumulation trends spanning decades to centuries. This makes it particularly valuable for understanding how carbon sequestration rates have varied over time, for validating models, and for building carbon baselines in blue carbon accounting.

The output of this method is a sedimentation or deposition rate (in $\text{cm}\cdot\text{yr}^{-1}$ or mm/a), derived from the radioactive decay profiles of ^{210}Pb across sediment layers. Combined with bulk density and organic carbon content (C_{org}), this allows another way to calculate the Carbon Accumulation Rate.

Field Procedure (Sediment Core Collection and Subsampling)

1. Core Extraction

Select representative monitoring sites within each stratum. Using a gouge auger, Russian peat corer, or vibracorer, extract undisturbed sediment cores to at least 1 m depth (or until refusal). Keep the sampler vertical and twist gently to shear roots.

2. Orientation and Labeling

Mark “top” and “bottom” of each core. Record GPS coordinates, date, and core ID in field logs.

3. Core Description

In the field or lab, describe core characteristics (color, layering, texture, root content) and photograph with a visible scale.

4. Subsampling Intervals

Section cores at 2 cm intervals for the upper 0–10 cm (dynamic layer) and 5 cm intervals for deeper layers, or per project protocol.

5. Preservation

Place each subsample in sealed, labeled containers. Store at ~4 °C or freeze within 24 hours. In remote areas, air-drying or vacuum-sealing can be used until analysis.

Laboratory Analysis

1. Bulk Density (BD)

Oven-dry at 60 °C until constant weight, record dry mass, and divide by sample volume (cm³).

2. Organic Carbon Content (%C_{org}) –

- Preferred: CHN elemental analyzer.
- Alternative: Loss-on-Ignition (LOI) with calibration to %C_{org}, correcting for inorganic carbon where present.

3. Isotope Analysis

- Measure ²¹⁰Pb activity using an alpha spectrophotometer with a PIPS detector.
- Calculate excess ²¹⁰Pb (²¹⁰Pb_{xs}) by subtracting supported ²¹⁰Pb from total ²¹⁰Pb.
- Develop age–depth models using either the Constant Flux–Constant Sedimentation (CF–CS) or Constant Rate of Supply (CRS) model, as appropriate.
- Determine sedimentation rate (Z) from the slope of the age–depth relationship (cm/yr).

A4.4 Deadwood

Deadwood comprises standing dead trees and downed woody debris (logs, branches, and fine fractions). Quantification relies on standardized, non-destructive field methods—tree inventory rules for standing dead with decay-class assignment, and direct measurements of fallen pieces—with limited subsampling where required. Biomass estimates are aggregated to the plot and reported as carbon stock using the adopted carbon fraction.

A4.4.1 Equipment for deadwood measurements

Standing Dead Trees (SDT) – dimensions and class

- Diameter tape or tree calipers for DBH, basal diameter, and top diameter estimates
- Measuring pole, clinometer, or laser rangefinder for total height (H).
- Machete/hand saw

Downed (Fallen) Wood

- Measuring tapes (30–50 m) to establish line-intersect transects and to record piece lengths.
- Digital calipers for end-diameters of pieces
- Aluminium downed-wood gauge to assign pieces to size classes (fine/small/medium/large).
- Hand/pruning saw for sub-sampling pieces

Fine Woody Debris (FWD)

- Quadrats or microplots (1 m² or 50 × 50 cm) for collection.
- Field balance (±0.5% accuracy) to record wet and dry masses; sample bags/labels for handling.

A4.4.2 Measurement of Standing Dead Trees

Standing dead trees are inventoried like live trees, with an integrity factor (DF) by decay class to reflect loss of twigs/branches and wood condition.

1. Identify all standing dead trees within the plot and confirm species if possible.
2. Measure diameter at breast height at 1.3 m above ground (or above prop roots if present) using a diameter tape.
3. Measure total height using a clinometer, measuring pole, or laser rangefinder.
4. Classify each tree into a decay class:
 - Class A: twigs/small branches present (DF = 0.9)
 - Class B: twigs absent; some large branches may remain (DF = 0.8)
 - Class C: bole/snags only, often broken-topped (DF = 0.7)

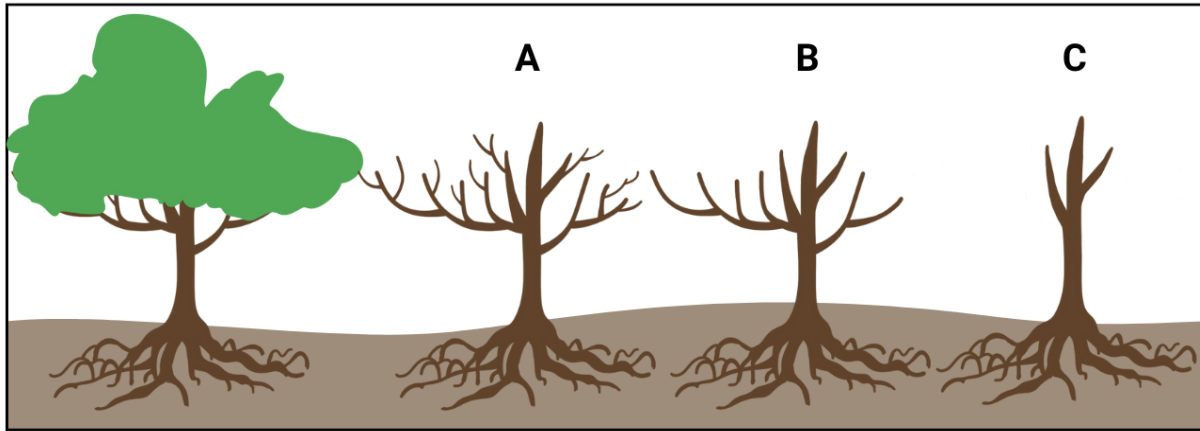


Figure 21: Stages of decay (Modified from SNI 7724:2019 Indonesian National Standards)

A4.4.3 Measurement of Fallen Logs

Fallen dead trees (trunks and large branches) are measured because they often hold a large share of dead wood carbon despite ongoing decay. Volume is estimated from their length and diameters, then converted to biomass using the applicable dead-wood density

1. Identify all large fallen trunks and branches (diameter ≥ 10 cm) clearly associated with original trees within the plot.
2. Record diameter at both ends (D_1 and D_2 , in cm) and total length (L , in cm).

A4.4.4 Sampling Fine Woody Debris

Fine woody debris (branches and twigs < 10 cm diameter) decomposes faster but can still hold significant carbon when abundant. These smaller pieces are directly weighed and dried to quantify their biomass.

1. Establish 1 m^2 quadrats (or 50×50 cm microplots in dense stands) at random points within the plot.
2. Collect all fine woody material (branches and twigs < 10 cm diameter) within each quadrat.
3. Place samples into labeled, sealed bags and record total wet weight in the field.
4. Oven-dry samples at $70\text{--}85^\circ\text{C}$ until constant weight (typically 48–72 hours).
5. Record the dry weight to determine final biomass.

A4.4.5 Estimating Biomass of Standing Dead Trees

The biomass of standing dead trees within the plot is determined using:

$$B_{SDT_tree}(kg) = a \times (DBH)^b \times DF \quad \text{Equation 29}$$

where:

- B_{SDT} is the estimated biomass (kg)
- DBH is the tree diameter at breast height (cm)
- a and b are species-specific allometric coefficients
- DF is the decay factor based on the assigned decomposition class (0.9, 0.8, 0.7 for classes A, B, C)

The estimated biomass is multiplied by the decay factor to adjust for wood loss due to decomposition.

The sum of the biomass of all standing dead trees in the plot to compute the total:

$$Total\ B_{SDT_plot}(Mg/ha) = \frac{\sum B_{SDT_tree}(kg)}{Area_{plot}(m^2)} \times 10 \quad \text{Equation 30}$$

Where

- $Area_{plot}(m^2)$ is the actual sampled area for standing dead trees
- $\times 10$ converts kg/m^2 to Mg/ha

A4.4.6 Estimating Biomass of Fallen Dead Trees

Fallen dead trees are measured by recording diameter at both ends and total length. These values are used to compute volume (cm^3) using the equation:

$$V = \frac{\pi \times (D_1^2 + D_2^2)}{8} \times L \quad \text{Equation 31}$$

where $D1$ and $D2$ are the diameters (cm) at both ends, and L is the total length (cm) of the tree. Biomass per log is obtained by multiplying volume by the applicable dead-wood density:

$$B_{FallenLogs}(kg) = \frac{V \times \rho_{dead\ wood}}{1000} \quad \text{Equation 32}$$

Where

- V is in cm^3

- $\rho_{dead\ wood}$ is the applicable dead-wood density in g/cm³. Where site-measured values are unavailable, the size-class density values provided in Table 1 may be used.

Table 1: Example dead-wood densities by size class (from Kauffman et al.; use site-measured values when available)

Size class (cm diameter)	DENSITY $\pm$ SE (g/cm ³) Note 1 g/cm ³ = 1 Mg/ m ³
< 0.64	0.48 $\pm$ 0.01
0.65 – 2.54	0.64 $\pm$ 0.02
2.55 – 7.6	0.71 $\pm$ 0.01
> 7.6	0.69 $\pm$ 0.02

The sum of the biomass of all fallen logs in the plot:

$$Total\ B_{FallenLogs}(Mg/ha) = \frac{\sum B_{FallenLogs}(for\ each\ log)\ (kg)}{Area_{plot}(m^2)} \times 10 \quad \text{Equation 33}$$

Where $Area_{plot}(m^2)$ is the actual/total sampled area of the fallen dead tree subplots within the main plot.

A4.4.7 Estimating Biomass of Fine Woody Debris and Small Branches

After all the small branches and woody fragments for the plot were gathered, oven-dried and weighed, the total dry biomass over the plot is computed using the following:

$$Total\ B_{FineDebris}(Mg/ha) = \frac{\sum Dry\ Weight\ of\ Fine\ Debris\ (kg)}{Area_{plot}(m^2)} \times 10 \quad \text{Equation 34}$$

Where $Area_{plot}$ is the total area of the fine-debris microplots in the plot (e.g., 3 quadrats $\times$ 0.5 $\times$ 0.5 m = 0.75 m²).

A4.4.8 Total Deadwood Carbon for the plot

Once biomass estimates for each component of dead wood (standing dead trees, fallen dead trees, and fine woody debris) are obtained, the total dead wood biomass density for the plot is calculated by summing the biomass of all components:

$$B_{Deadwood}(Mg/ha) = B_{SDT} + B_{FallenLogs} + B_{FineDebris} \quad \text{Equation 35}$$

To estimate the carbon stock in dead wood, apply the carbon fraction to the total biomass:

$$C_{Deadwood}(Mg/ha) = B_{Deadwood}(Mg/ha) \times CF \quad \text{Equation 36}$$

The default value for carbon concentration of dead wood is 0.5.

A4.5 Litter

Litter comprises recently fallen non-woody material—leaves, flowers, fruits/propagules, and bark fragments—accumulated on the soil surface. When included in accounting, quantification is by collection from fixed microplots within the main plots, drying to constant weight to obtain biomass, and conversion to carbon using the adopted carbon fraction.

A4.5.1 Equipment for sampling Litter

Microplots / Quadrat Frames

- Rigid frames for destructive sampling: 30 × 30 cm to 1 m²

Collection Tools & Containers

- Hand trowel or scoop; forceps for small fragments.
- Pre-labelled, heavy-duty plastic bags or lidded containers; waterproof markers and sample IDs.
- Optional sieve/mesh (≥5 mm) to exclude sediment and very fine non-litter particles during collection.

Weighing & Handling

- Portable field balance (±0.5% accuracy) to record total wet mass when bulk samples cannot be transported; permits taking a representative subsample for laboratory drying.
- Secondary bags for subsamples; aluminum foil or paper bags for oven drying.
- Cooler for transport in hot/wet conditions.

A4.5.2 Litter Sampling

If included in the assessment, here are the detailed procedures for field data collection and analysis for mangrove litter.

How to Collect Samples:

1. Microplot Establishment

Sampling begins with establishing microplots, typically 0.5 × 0.5 meters (0.25 m²) or, in stands with heavier detritus loads, 1 × 1 meter (1 m²) quadrats. These are randomly or systematically placed within the main sampling plots to represent site variability. Within each quadrat, carefully gather all visible organic surface material, including leaves, flowers, fruits, seeds, and propagules, while excluding woody particles, living plant material, sediments, and non-organic debris.

2. Litter Collection

Collected litter is placed into pre-labeled, durable bags marked with site, plot, date, and sample number to ensure proper traceability. Due to the often-large volume of litter relative to drying capacity, the wet weight of each entire sample is recorded in the field using a portable scale. If drying capacity is a limitation, a well-mixed subsample may be taken for laboratory drying and used to establish a wet-to-dry conversion ratio.

3. Sample Storage and Drying

Transport samples promptly to the laboratory, storing them cool to slow decomposition if drying cannot begin immediately. Dry each sample (or subsample) in an oven set at 60 °C, continuing for 24 to 72 hours until the mass stabilizes (constant weight). Higher temperatures such as 105 °C should be avoided for carbon stock estimation, as they may oxidize organic matter and underestimate carbon content.

4. Subsampling

If subsampling was conducted, determine the wet-to-dry ratio from the dried subsample, then apply this ratio to the wet weight of the bulk sample to estimate total dry biomass.

A4.5.3 Total Litter Carbon for the plot

Once the litter samples collected were dried and weighed, the biomass for the plot is computed using:

$$B_{Litter}(Mg/ha) = \frac{\sum \text{Dry mass of litter (kg)}}{Area_{plot}(m^2)} \times 10 \quad \text{Equation 37}$$

The carbon stock for litter is derived by applying the carbon fraction to the measured biomass:

$$C_{Litter} = B_{Litter} \times CF \quad \text{Equation 38}$$

For litter collected from nested microplots, use the total sampled microplot area in the denominator, or average microplot-level litter densities under the sampling design. Do not divide the collected litter mass by the full tree-plot area unless litter was sampled over that entire area.

A.5 Carbon Stock Estimation for Mangrove Project Area

The total carbon stock within a mangrove project area is calculated by systematically aggregating carbon stocks from individual plots to strata and then to the entire project area. This ensures consistency in reporting at different scales and provides estimates both as Mg/ha (per unit area) and as total Mg (absolute carbon stock).

A5.1 Compute Total Carbon Stock per Plot (Mg/ha)

For each plot, calculate the carbon stock for each measured component (e.g., aboveground biomass, belowground biomass, soil organic carbon, litter, and dead wood). The calculations follow the methods described for each pool, expressed in Mg/ha.

- a. Measure Carbon Stock for Each Pool:

C_{AGB} (Mg/ha): Aboveground biomass carbon stock per hectare.

C_{BGB} (Mg/ha): Belowground biomass carbon stock per hectare.

C_{SOC} (Mg/ha): Soil organic carbon stock per hectare.

C_{Litter} (Mg/ha): Litter carbon stock per hectare.

$C_{Deadwood}$ (Mg/ha): Dead wood carbon stock per hectare.

- b. Sum Carbon from All Pools:

$$C_{Plot}(Mg/ha) = C_{AGB} + C_{BGB} + C_{SOC} + C_{DeadWood} + C_{Litter} \quad \text{Equation 39}$$

A5.2 Aggregate Carbon Stock to Stratum Level

For stratified project areas, carbon stock is aggregated to the stratum level to account for spatial variations (e.g., tidal zones, canopy structure, vegetation type).

- a. Calculate Average Carbon Stock per Stratum:

Average carbon stock for all plots within a stratum:

$$C_{Stratum}(Mg/ha) = \frac{\sum C_{Plot}(Mg/ha)}{Number\ of\ Plots\ in\ the\ Stratum} \quad \text{Equation 40}$$

- b. Calculate Total Carbon Stock for the Stratum:

Multiply the average carbon stock by the total area of the stratum:

$$C_{Stratum}(Mg) = C_{Stratum}(Mg/ha) \times Stratum\ Area\ (ha) \quad \text{Equation 41}$$

A5.3 Compute Total Carbon Stock for the Project Area

- a. Sum Carbon Stocks Across All Strata:

Total carbon stock for the project area is the sum of carbon stocks across all strata:

$$C_{Project\ Area}(Mg) = \sum C_{Stratum}(Mg) \quad \text{Equation 42}$$

- b. Calculate Average Carbon Stock for the Project Area:

The average carbon stock for the project area (reported in Mg/ha) is calculated as the weighted average:

$$C_{Project\ Area}(Mg/ha) = \frac{\sum [C_{Stratum}(Mg/ha) \times Stratum\ Area\ (ha)]}{Total\ Project\ Area\ (ha)} \quad \text{Equation 43}$$

A5.4 Uncertainty in Carbon Stock Estimation

Accurate reporting of carbon stock estimates requires not only measuring each pool but also quantifying the uncertainty associated with those measurements.

A5.4.1 Error Propagation

a. Estimate Carbon Stock and Uncertainty for Each Carbon Pool

For each carbon pool—Aboveground Biomass (AGB), Belowground Biomass (BGB), Soil Organic Carbon (SOC), and others where included—calculate:

$$Carbon\ Stock_{Pool} = Mean \pm Standard\ Error \quad \text{Equation 44}$$

Where SE (standard error) is computed from replicate plots or samples within the stratum.

- AGB and BGB: Estimated from field plots using allometric equations, biomass expansion factors, or root-to-shoot ratios.
- SOC: Estimated from bulk density, carbon concentration (%C_{org} from CHN or LOI), and soil depth.

b. Combine Uncertainty from All Carbon Pools (Error Propagation)

Once uncertainties are calculated for each pool, combine them using the root-sum-square (RSS) method:

$$SE_{Total\ Pools} = \sqrt{(SE_{AGB})^2 + (SE_{BGB})^2 + (SE_{SOC})^2 + \dots} \quad \text{Equation 45}$$

This provides the stand-level or plot-level total carbon stock uncertainty, typically per hectare.

c. Account for Uncertainty in Area Estimates

Area estimates derived from GIS or remote sensing also carry uncertainty, which should be reported as:

$$Area_{Pool} = Mean\ Area \pm Standard\ Error_{Area} \quad \text{Equation 46}$$

d. Propagating Stock and Area Uncertainty

To calculate total uncertainty for the project:

$$SE_{total} = Total\ Carbon\ Stock \times \sqrt{\left(\frac{SE_{Stock}}{Carbon\ Stock}\right)^2 + \left(\frac{SE_{Area}}{Area}\right)^2} \quad \text{Equation 47}$$

e. Report Total Carbon Stock with Uncertainty

The final result is presented as:

$$Total\ Carbon\ Stock = Mean \pm SE_{total} \quad \text{Equation 48}$$

Values should be presented with clear units (e.g., Mg C/ha), and where applicable, converted to Mg CO₂ using a 3.67 molar mass factor.

Root-sum-square propagation assumes independent errors. Where estimates share a model, carbon fraction, laboratory calibration or area estimate, account for that dependence. When combining strata, apply the corresponding area weights and include area uncertainty where material, following main Chapter 6.

A5.4.2 Monte Carlo Simulation (Optional Advanced Method)

Monte Carlo Simulation is a statistical method used to account for uncertainty by running thousands of simulations that generate a range of possible outcomes. In the context of carbon stock assessment, Monte Carlo Simulation helps to account for uncertainties in different inputs (e.g., tree biomass, area estimates, carbon fraction, emission factors) by randomly sampling from probability distributions associated with each uncertain parameter. The simulation then provides a probability distribution of possible outcomes, allowing the user to estimate both the mean and the uncertainty (standard deviation, confidence intervals) of the total carbon stock.

Monte Carlo Simulation Steps Summarized:

- Define Uncertain Inputs: Identify key inputs (e.g., tree biomass, area, carbon fraction) and assign probability distributions.
- Run Random Simulations: Perform thousands of iterations by randomly sampling from the distributions and calculating total carbon stock for each iteration.
- Analyze Output: Calculate the mean, standard deviation, and confidence intervals from the simulation results.

- d. Report Results: Present the carbon stock with uncertainty (e.g., mean $\pm$ standard deviation or confidence intervals).
- e. Visualize: Use graphical tools to represent the uncertainty range and most likely values.

A.6 Carbon Sink (Sequestration Rate) Estimation in Mangrove Ecosystems

Estimating carbon sequestration in mangroves requires quantifying the net annual increase in stored carbon across different carbon pools—most notably aboveground biomass, belowground biomass, and soil organic carbon. Depending on available data, monitoring design, and ecosystem characteristics, two principal methods are used: the stock-difference method and the gain–loss method.

The stock-difference method involves measuring carbon stocks in each relevant pool at two time points and calculating the net change over time. This approach is well-suited for monitoring carbon accumulation in mangrove restoration or protection projects where long-term plot-based measurements are feasible. It is particularly robust for aboveground biomass and soil carbon, as these pools tend to show measurable change over multi-year periods. When baseline and subsequent carbon stock measurements are obtained through standardized field methods, this approach offers a direct and transparent estimate of sequestration.

In contrast, the gain–loss method estimates annual carbon fluxes by measuring gains—such as tree biomass growth, litterfall, and sediment deposition—and subtracting losses due to decomposition or disturbance. In mangroves, this method is commonly used when high-resolution process data are available, including tree increment data (e.g., annual DBH measurements), surface elevation change (e.g., using SETs and marker horizons), and sediment carbon content. Isotope-based dating methods (e.g., ^{210}Pb , ^{137}Cs) may also support estimation of long-term carbon burial in mangrove soils. The gain–loss method is especially useful for characterizing carbon dynamics at finer temporal and ecological scales, including rapidly accreting or degrading sites.

Both methods are valid for estimating mangrove sequestration rates, and in many cases, a combination of the two is applied—using stock-difference for biomass pools and gain–loss for soil or sediment carbon. The selection of approach depends on project scope, monitoring capacity, and the target carbon pools. In all cases, the estimation should aim to meet minimum accuracy thresholds required for credible carbon accounting and potential crediting.

A6.1 Stock-Difference Method for Mangroves

The stock-difference approach requires field-based measurements from the same sampling plots at two points in time (baseline and monitoring year). These values are then annualized and scaled to the project area.

Field-derived carbon stock values used here must come from consistent plot locations, methodologies, and stratification categories, as defined in the field data collection and stock estimation chapters (A.4 and A.5). Where relevant, the mean carbon density (e.g., Mg C/ha) per pool per stratum is used and scaled by the area represented by the sample plots.

A6.1.1 Carbon Stock Change in Aboveground Biomass

Aboveground biomass includes all living vegetation above the soil surface, primarily mangrove trees. To calculate carbon stock change in AGB, repeat measurements of DBH, height, and species are required in the same sample plots over a defined time interval.

Carbon stock per plot is calculated using allometric equations and then scaled to Mg C/ha. The mean AGB carbon density per stratum or project area can then be used in the stock-difference calculation.

Stock-difference formula:

$$\Delta C_{AGB} = \frac{(C_{t2,AGB} - C_{t1,AGB}) \times A}{t_2 - t_1} \quad \text{Equation 49}$$

Where:

- ΔC_{AGB} = Annual change in AGB carbon (Mg C/yr)
- $C_{t1,AGB}, C_{t2,AGB}$ = Mean AGB carbon stock at t1 and t2 (Mg C/ha)
- A = Area of ecosystem represented (ha)
- $t_2 - t_1$ = Time interval between measurements (years)

This estimate can be stratified by vegetation type, age class, or other biophysical characteristics to improve accuracy.

A6.1.2 Carbon Stock Change in Belowground Biomass

Belowground biomass represents the root systems of mangrove vegetation. BGB is commonly estimated using root-to-shoot ratios applied to AGB values, or site-specific allometric models where available.

Formula:

$$\Delta C_{BGB} = \frac{(C_{t2,BGB} - C_{t1,BGB}) \times A}{t_2 - t_1} \quad \text{Equation 50}$$

The same spatial and temporal principles apply as with AGB. Care should be taken to ensure consistency in root estimation approaches across measurement years.

A6.1.3 Carbon Stock Change in Soil/Sediment

Soil organic carbon constitutes a major portion of the total carbon stock in mangrove ecosystems. SOC is calculated using the measured bulk density, carbon content, and depth of sampled soil cores.

SOC stock at t1 and t2 are estimated from composite samples of multiple plots. These are converted to mean carbon densities (Mg C/ha) and used in the following formula:

Formula:

$$\Delta C_{SOC} = \frac{(C_{t2,SOC} - C_{t1,SOC}) \times A}{t_2 - t_1} \quad \text{Equation 51}$$

Sampling depth should be consistent across time periods (e.g., 1 meter) or reported separately by depth intervals if different.

A6.1.4 Carbon Stock Change in Included Deadwood and Litter Pools

Include deadwood and litter in accordance with main Section 4.3.3. Any exclusion shall satisfy main Section 10.4, including its cumulative significance test relative to net GHG benefits before leakage. Do not exclude an adverse pool change where doing so would overstate benefits. For included pools, use consistent sampling locations and appropriate monitoring intervals.

Formula:

$$\Delta C_{dead+litter} = \frac{(C_{t2} - C_{t1}) \times A}{t_2 - t_1} \quad \text{Equation 52}$$

Due to high variability and natural fluctuation in these pools, it is advisable to increase sample size or apply conservative estimates, especially if the pool exhibits high temporal variability or is expected to be a small but potentially significant component of the overall carbon budget.

A6.1.5 Estimating Total and Annual Sequestration from Stock Change

Once each carbon pool's annual change has been estimated, the net annual sequestration is the sum across all included pools:

$$\Delta C_{total} = \Delta C_{AGB} + \Delta C_{BGB} + \Delta C_{SOC} + \Delta C_{dead+litter} \quad \text{Equation 53}$$

This estimate is expressed in Mg C/yr. To convert to CO₂-equivalent:

$$\Delta CO_2e = \Delta C_{total} \times 3.67 \quad \text{Equation 54}$$

Where 3.67 is the molecular weight ratio of CO₂ to C. This conversion expresses the carbon-stock change as a CO₂ quantity. A stock increase represents a removal, while a stock decrease represents an emission. Apply the emissions-positive/removals-negative convention when entering the result into the GHG balance. Calculate project net GHG benefits relative to the baseline, including applicable project emissions and leakage, in accordance with main Section 9.6. The converted stock change alone does not establish an issuable credit quantity, and any gain or loss already represented in the stock change shall not be counted again.

The accuracy of this estimate is contingent on plot representativeness, measurement consistency, and time interval. Annualization should only be applied when the time difference (t₂ – t₁) is at least 1 year, preferably 2–5 years for greater reliability.

A6.2 Gain–Loss Method for Mangroves

The Gain–Loss method estimates net annual carbon sequestration by balancing measured carbon gains (e.g., biomass growth, sediment carbon burial) against carbon losses (e.g., decomposition, disturbance, greenhouse gas emissions).

This method is especially useful when:

- Permanent plots provide growth or productivity data but long-term repeated stock measurements (stock-difference method) are not available;

- Sediment burial rates are known from SET–MH installations or radiometric dating; or
- Estimating fluxes directly is more feasible than repeated total stock assessments.

The general formula applied is:

$$\Delta C = \Delta C_{Gain} - \Delta C_{Loss} \quad \text{Equation 55}$$

Where:

- ΔC = Net annual carbon sequestration (Mg C/yr)
- ΔC_{Gain} = Annual carbon gains (Mg C/yr)
- ΔC_{Loss} = Annual carbon losses (Mg C/yr)

Inputs are derived from the field measurements and laboratory analyses described in Section A.4.

Calculate gains and losses separately for each stratum. Express every term in Mg C/yr, multiplying any per-hectare rate by the corresponding stratum area once. Sum the stratum totals to obtain the project total.

A6.2.1 Estimating Carbon Gains

a. Tree Biomass Increment (Above- and Belowground)

Biomass gains are estimated from tree growth rates in permanent monitoring plots or published productivity values. Allometric equations are applied to calculate annual biomass increments.

$$\Delta C_{biomass}(\text{Mg C/yr}) = \Delta G_{AGB} \times CF \times (1 + R) \times A \quad \text{Equation 56}$$

Where:

- ΔG_{AGB} = Annual growth rate of AGB (Mg biomass/ha/yr)
- CF = Carbon fraction (commonly 0.47–0.50)
- R = Root-to-shoot ratio
- A = Area covered (ha)

Growth rate values may be calculated from species-specific monitoring data across plots or taken as plot-level averages, depending on data availability. For standardization, average increment per tree species may be multiplied by density and scaled up to plot or project level.

b. Soil Carbon Accumulation via Sediment Accretion

Mangrove soils accumulate carbon through vertical sediment accretion. Sediment accretion is measured using marker horizons, while Surface Elevation Tables measure surface elevation change. Accretion and sediment carbon density are used to estimate carbon accumulation.

$$\Delta C_{soc}(\text{Mg C/yr}) = BD \times Z \times C_{org} \times 100 \times A \quad \text{Equation 57}$$

Where:

- BD = Bulk density (g/cm^3)
- Z = Accretion rate (cm/yr)
- C_{org} = Organic carbon mass fraction ($\text{g C/g dry sediment}$), expressed as a decimal; e.g., 0.02 for 2%
- A = Area (ha)

The factor 100 converts g C/cm^2 to Mg C/ha .

This calculation estimates carbon accumulation associated with sediment accretion. It does not by itself establish long-term net carbon burial. Account for subsequent losses where applicable, without subtracting losses already represented in a net burial estimate.

Alternatively, the Carbon Accumulation Rate (CAR) from literature or derived from dated sediment cores can be used:

$$\Delta C_{soc}(\text{Mg C/yr}) = CAR \times A \quad \text{Equation 58}$$

Where:

- CAR = Carbon accumulation rate (Mg C/ha/yr)
- A = Stratum area (ha)

c. Radiometric Dating for Burial Rates

Radiometric dating using ^{210}Pb provides a long-term perspective on sedimentation and carbon burial in mangrove soils. While more resource-intensive than SET-MH, it is particularly suited for:

- Long-term restoration monitoring;
- Peat-forming mangroves with deep organic deposits; and
- Projects requiring validation of accretion over decadal scales.

The following parameters are needed:

- BD = Bulk density (g cm^{-3})
- $\%C_{org}$ = Organic carbon content (fraction of dry mass)
- Z = Sedimentation rate (cm yr^{-1}) derived from ^{210}Pb age–depth models

The Carbon Accumulation Rate for each depth interval k is calculated as:

$$CAR_k = BD_k \times C_{org,k} \times Z_k \quad \text{Equation 59}$$

Where:

- CAR_k = Carbon accumulation rate in interval k ($\text{g C cm}^{-2} \text{ yr}^{-1}$)
- BD_k = Bulk density of interval k (g cm^{-3})
- $C_{org,k}$ = Organic carbon fraction in interval k ($\text{g C per g dry mass}$)
- Z_k = Sedimentation rate for interval k (cm yr^{-1})

Convert to $\text{Mg C ha}^{-1} \text{ yr}^{-1}$:

$$CAR_{ha} = CAR_k \times 100 \quad \text{Equation 60}$$

If the sedimentation rate is uniform across the core (as in the CF–CS model), a single Z value may be applied to all intervals.

A6.2.2 Estimating Carbon Losses

Carbon losses represent the release of carbon from the ecosystem and must be subtracted from gains. Losses are categorized as follows:

a. Decomposition and Respiration

Losses from litter decomposition or root turnover can be estimated as:

$$C_{loss,resp} = M_{decomp} \times CF \times A \quad \text{Equation 61}$$

Where:

- $C_{loss,resp}$ = Annual carbon loss for the stratum (Mg C/yr)
- M_{decomp} = Annual dry biomass or litter mass decomposed per hectare ($\text{Mg dry biomass/ha/yr}$)
- CF = Carbon mass fraction, expressed as a decimal
- A = Stratum area (ha)

Decomposition rates may be sourced from site studies or literature. Values typically range from 0.2–0.7 yr⁻¹ for mangrove litter.

Count decomposition as an ecosystem carbon loss only to the extent that carbon leaves the included accounting pools. Transfers from biomass or litter into an included soil carbon pool shall not be counted as ecosystem losses. Do not subtract a loss separately where it is already reflected in the stock-change or net burial estimate.

b. Disturbance and Land-Use Change

Losses from degradation, logging, or natural disturbance events (e.g., typhoons) can be estimated based on the proportion of carbon lost and frequency of such events. Where data are unavailable, conservative IPCC default loss factors may be used.

c. Drainage and Oxidation of Soils

If mangrove soils are disturbed (e.g., by trenching, aquaculture, or conversion), aerobic oxidation results in CO₂ emissions. Estimate:

$$CO_2 = ADR \times EF_{drain} \quad \text{Equation 62}$$

Where:

- ADR = Area affected by drainage (ha)
- EF_{drain} = Emission factor (Mg CO₂ /ha/yr), e.g., from IPCC 2014

This equation produces an annual emission in Mg CO₂/yr. If included in the carbon-mass loss subtotal, convert it to Mg C/yr by multiplying by 12/44. Do not add the same emission again as a separate CO₂ term in the final GHG balance.

d. Methane (CH₄) and Nitrous Oxide (N₂O) Emissions

In high-nutrient or disturbed mangroves, apply emission factors from IPCC (2014) or peer-reviewed sources when direct measurement is not feasible.

Account for CH₄ and N₂O separately from the Mg C gain–loss subtotal. Convert these emissions to CO₂-equivalents using the applicable GWP values and include them in the GHG balance under main Section 9.6.

A6.2.3 Calculating and Reporting Sequestration Rate

Once annual gains and losses have been quantified for each stratum on a consistent carbon-mass basis, calculate its net annual carbon gain as follows:.

$$\Delta C_{net,i} = \Delta C_{Gain,i} - \Delta C_{Loss,i} \quad \text{Equation 63}$$

Where:

- i = Stratum index
- $\Delta C_{net,i}$ = Net annual carbon gain in stratum i (Mg C/yr)
- $\sum \Delta C_{Gain,i}$ = Sum of annual carbon gains across included pools in stratum i (Mg C/yr)
- $\sum \Delta C_{Loss,i}$ = Sum of annual carbon losses from included accounting pools in stratum i (Mg C/yr)

a. Aggregation Across Strata

Project net annual carbon gain is calculated by summing the stratum totals. Each stratum total already includes its area.

$$C_{net,project} = \sum_{i=1}^n \Delta C_{net,i} \quad \text{Equation 64}$$

Where:

- $C_{net,project}$ = Project net annual carbon gain (Mg C/yr).
- $\Delta C_{net,i}$ = Net annual carbon gain in stratum i (Mg C/yr)
- n = Number of strata

b. Conversion to CO₂-equivalent

To express results in terms of CO₂-equivalent for reporting and crediting purposes:

$$\Delta CO_2e_{net} = C_{net,project} \times 3.67 \quad \text{Equation 65}$$

Where 3.67 is the molecular weight ratio of CO₂ to C.

This conversion expresses net carbon gain as a CO₂ removal quantity; it does not by itself establish project net GHG benefits or an issuable credit quantity. Calculate project net GHG benefits relative to the baseline, including applicable project emissions and leakage, under main Section 9.6. Apply the emissions-positive/removals-negative convention when entering the removal into the GHG balance, and avoid counting any gain or loss twice.

c. Temporal Averaging and Reporting Period

If sequestration estimates are based on multi-year measurements or modeled averages, the result should be annualized over the relevant interval. Annualization should only be applied where the monitoring interval is at least one year, and preferably two to five years for improved accuracy.

All reported values must:

- Be clearly linked to the field and laboratory measurements described in A.4;
- Identify the calculation method used for each pool (direct measurement, modeled growth, literature-based values);
- Present uncertainty estimates consistent with the procedures in A.8 Uncertainty and QA/QC; and
- Use consistent units (e.g., Mg C/ha/yr for rates; Mg C/yr or t CO₂e/yr for project totals).

d. Integration with Stock-Difference Estimates

If the project applies both the stock-difference and gain–loss methods (e.g., stock-difference for biomass pools and gain–loss for SOC burial), results should be combined at the pool level before calculating the net total. In such cases:

- Avoid double-counting by ensuring each pool is only represented once;
- Apply uncertainty combination procedures across all pools and strata.

A.7 Measurement of Direct Carbon Emissions (CO₂ FLUX)

Direct carbon flux measurement quantifies the exchange of CO₂ between mangrove ecosystems and the atmosphere. While most mangrove carbon dynamics are captured through biomass and soil carbon stock assessments, certain project contexts—such as degradation, soil disturbance, or conversion—may require direct measurement of CO₂ efflux from soils or sediments. This section focuses on practical field methods that can be implemented in mangrove project settings, with primary emphasis on the static chamber technique, which is widely used, cost-effective, and suitable for small- and medium-scale projects. More complex approaches such as eddy covariance are described briefly for completeness but are not required for most project applications.

A7.1 Measurement Approaches

Carbon flux from mangrove soils is generally partitioned into two categories:

1. Soil CO₂ efflux, resulting from root respiration and microbial decomposition.
2. Net ecosystem exchange (NEE), representing the balance between ecosystem respiration and photosynthetic CO₂ uptake.

Most blue carbon project needs relate to soil CO₂ efflux, which can be measured using chamber systems applied directly at the sediment surface. NEE measurements using eddy covariance systems are more complex and are generally outside the scope of project-level monitoring unless part of long-term research infrastructure.

A7.1.1 Static Chamber Method (Soil CO₂ Efflux)

The static chamber technique encloses a small portion of the soil or sediment surface to track changes in CO₂ concentration over a short period. It is suitable for tidal wetlands, simple to deploy, and requires portable analyzers or laboratory gas chromatography.

Chamber Design and Installation

A chamber consists of a gas-tight enclosure fitted with a sampling port, thermometer, and small fan for internal air mixing. A base collar is installed 5–10 cm into the sediment several days before measurement to minimize disturbance. The chamber is placed over the collar and sealed using a water channel or gasket to ensure an airtight fit.

Select the chamber configuration according to the process being measured. A transparent chamber enclosing vegetation under light measures net CO₂ exchange within its footprint, including photosynthesis and respiration. An opaque chamber enclosing vegetation measures ecosystem respiration under the measurement conditions. For soil or sediment CO₂ efflux, define and document the vegetation treatment so that the measured flux is clearly identified. These measurements shall not be used interchangeably.

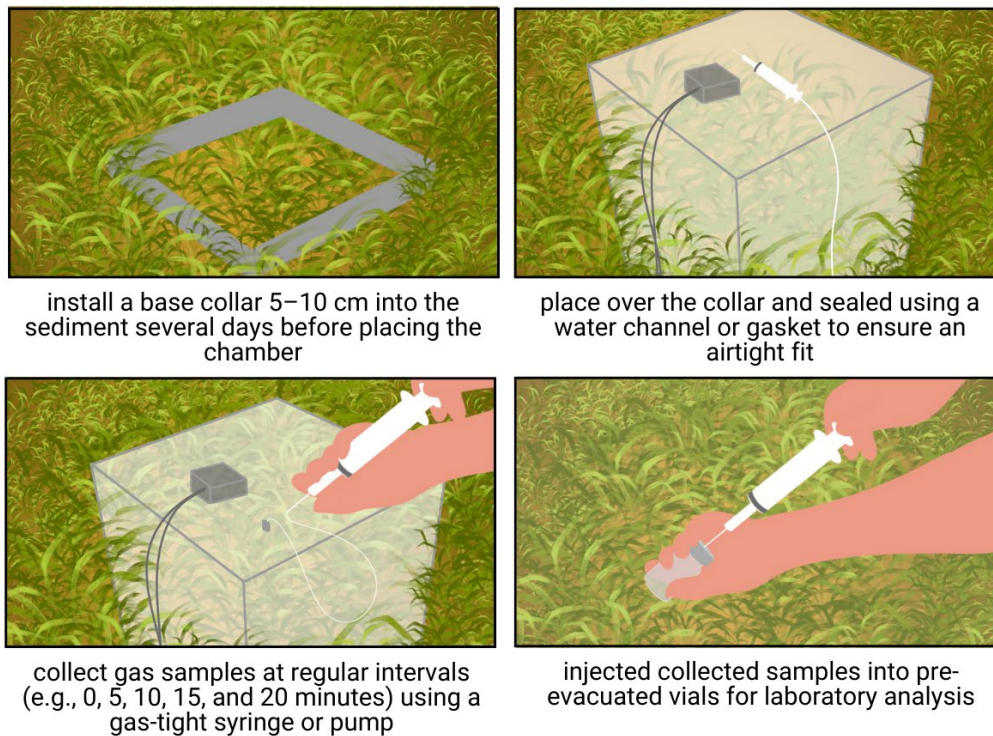


Figure 22: Sample Static Chamber set-up

Field Measurement Procedure

Schedule measurements to represent relevant diurnal, seasonal and tidal conditions. Document recent disturbances and use a setup appropriate to the surface condition being measured. After sealing the chamber to the collar, gas samples are collected from the chamber headspace at regular intervals (e.g., 0, 5, 10, 15, and 20 minutes). Sampling is done using a gas-tight syringe or pump, with samples injected into pre-evacuated vials for laboratory analysis or analyzed immediately using a portable CO₂ detector if available.

The rate of change in chamber CO₂ concentration represents the flux for the documented chamber configuration and enclosed surface; identify whether it is soil or sediment efflux, ecosystem respiration, or net CO₂ exchange. Temperature inside the chamber is monitored to correct for thermal expansion of air, and the chamber fan is operated briefly at the start of measurement to homogenize headspace gases.

Flux Calculation

Soil CO₂ flux is calculated from the linear rate of change in headspace CO₂ concentration using the Ideal Gas Law:

$$F_{CO_2} = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \frac{P}{RT} \times M_{CO_2} \times 3600 \quad \text{Equation 66}$$

Where:

- F_{CO_2} = mass flux rate of CO₂ (mg CO₂ /m²·h)
- $\Delta C/\Delta t$ = Rate of change in CO₂ mole fraction, expressed in mol/(mol·s). Convert a slope measured in ppm/s or μmol/(mol·s) by multiplying by 10⁻⁶ before substitution.
- V = effective chamber volume (m³)
- A = chamber footprint area (m²)
- P = atmospheric pressure (Pa, where 1 atm = 101,325 Pa)
- R = universal gas constant (8.314 Pa·m³/(mol·K))
- T = chamber air temperature (K = °C+273.15)
- M_{CO_2} = Molar mass of CO₂ (44,010 mg/mol)
- 3600 = Time conversion factor (seconds per hour)

For molar flux, omit M_{CO_2} and the factor 3600. The resulting flux is in mol CO₂/(m²·s); multiply by 10⁶ for μmol CO₂/(m²·s) or by 10³ for mmol CO₂/(m²·s).

Integrate fluxes over representative diurnal, tidal and seasonal conditions to estimate annual CO₂ emissions. Convert annual emissions from Mg CO₂/ha/yr to Mg C/ha/yr by multiplying by 12/44 where a carbon-mass expression is required. Include these emissions in project accounting only where they are not already represented in the stock-change or gain-loss estimate. Positive flux indicates CO₂ emission; negative flux indicates CO₂ uptake.

Applicability in Mangroves

Chamber techniques are appropriate for measuring:

- CO₂ emissions from disturbed or restored soils
- Efflux associated with degradation or hydrological change
- Seasonal respiration patterns under varying inundation regimes

They are not sensitive to lateral dissolved carbon fluxes, which are not captured by atmospheric measurements but are acknowledged as part of broader carbon budgets.

A7.1.2 Eddy Covariance (Ecosystem-Scale CO₂ Exchange)

Eddy covariance (EC) systems measure continuous, high-frequency exchanges of CO₂ between the entire mangrove ecosystem and the atmosphere. A tower equipped with a 3D sonic anemometer and infrared gas analyzer is installed above the canopy, allowing direct quantification of net ecosystem exchange (NEE).

While EC provides comprehensive ecosystem-level CO₂ flux data, it requires specialized installation, complex data processing, and significant maintenance. It is best suited for long-term ecological research or national GHG inventories rather than routine blue carbon project monitoring. Tidal influence, salinity, and complex wind patterns in mangrove environments also require advanced footprint modeling and turbulence filtering.

For most project-level applications, EC is acknowledged as a potential supplementary method but is not required nor expected.

A7.1.3 Annual Emissions and Reporting

When chamber measurements are conducted, individual flux measurements are integrated over time, accounting for tidal stage, seasonality, soil temperature, and moisture. Annual emissions are calculated as:

$$E_{annual} = 10^{-5} \sum_{i=1}^n (F_{CO_2,i} \times \Delta t_i) \quad \text{Equation 67}$$

Where:

- E_{annual} = Annual CO₂ emissions (Mg CO₂/ha/yr).
- $F_{CO_2,i}$ = Representative flux for interval i (mg CO₂/(m²·h)).
- Δt_i = Duration represented by interval i (hours), with the intervals covering the reporting year.

The factor 10⁻⁵ converts mg/m² to Mg/ha.

Converted from CO₂ to carbon as:

$$C_{annual} = \frac{E_{annual}}{3.67} \quad \text{Equation 68}$$

The result is reported in Mg C/ha/yr, with metadata including sampling frequency, chamber specifications, and lab equipment.

A7.1.4 Uncertainty Considerations

Major sources of uncertainty include chamber leakage, temperature-induced pressure changes, tidal variation, and analytical precision. Individual flux measurements should be replicated across the plot or stratum, and uncertainty should be reported using standard error propagation or Monte Carlo approaches consistent with the broader uncertainty chapter of this methodology.

A.8 Uncertainty and QA/QC

This section describes the sources of uncertainty in mangrove carbon accounting, the precision targets and reporting requirements, and the quality assurance and quality control (QA/QC) practices that help reduce errors and improve credibility. For calculation procedures, refer to Section A5.4.

A8.1 Sources of Uncertainty

Uncertainties in mangrove carbon assessments arise from three primary domains:

Measurement Uncertainty

Measurement Uncertainty refers to errors in field measurements and laboratory analyses. For example, inaccuracies may stem from improperly calibrated DBH tapes or inconsistently measured tree height. Soil core compaction, instrument drift, and inconsistent application of laboratory procedures (e.g., Loss on Ignition without correcting for inorganic carbon) can introduce systematic or random error. If parameters like wood density or bulk density are not measured directly and instead taken from literature, the values may not reflect site-specific variability, thus affecting precision.

Model Uncertainty

Model Uncertainty arises from estimation methods and assumptions. This includes the structural uncertainty inherent in allometric models and biomass expansion factors. The use of default carbon fractions (e.g., 0.47 for dry biomass) may not accurately represent local species or site conditions. Additionally, misclassification in remote sensing or GIS-based stratification can lead to incorrect area delineation, thereby affecting calculated stock or emission values.

Sampling Uncertainty (Variability)

Sampling Uncertainty (Variability) results from natural heterogeneity within mangrove systems. Differences in hydrology, species composition, and disturbance regimes can lead to considerable

variation in carbon pools. Since only a finite number of sample plots are collected, sampling error is introduced when generalizing to the whole project area. Temporal variability, such as seasonal changes or recovery post-disturbance, further complicates estimates over time.

Area Estimation Uncertainty

Area estimation uncertainty arises from errors in delineating mangrove ecosystem extent and project strata. Sources include spatial resolution, classification errors, boundary delineation, georeferencing inaccuracies, and differences in tidal conditions or image acquisition dates.

Where ecosystem extent is derived from remote sensing or GIS-based classification, the accuracy of area estimates shall be assessed using appropriate reference data and validation procedures. Area uncertainty shall be quantified where relevant and incorporated into project-level carbon stock and GHG estimates in accordance with Chapter 6 of the Main Text.

A8.2 Reporting uncertainty in stocks and sinks

Transparent reporting is essential to ensure credibility. The standard convention is to express uncertainty as a 95% confidence interval, either:

- As a percentage of the mean
- As an absolute range (e.g., $\pm$ Mg C/ha)
- As minimum and maximum bounds

Carbon stocks are generally reported in Mg C/ha for a specified soil depth. For GHG accounting, this can be converted to Mg CO₂/ha using the molar mass ratio ($\times 3.67$).

State the adopted precision target, confidence level and whether the percentage represents confidence-interval half-width or full width. Assess and propagate uncertainty in accordance with main Chapter 6. Apply any uncertainty deduction only as required by the applicable certification framework.

When uncertainty is high or when using defaults, projects should apply the principle of conservatism—reporting values that are more likely to understate than overstate GHG benefits.

A8.3 Recommended QA/QC Procedures

Quality Assurance (QA) and Quality Control (QC) are necessary to minimize errors, ensure transparency, and meet verification standards. The following procedures apply throughout the project lifecycle:

1. **Field Data Quality Checks:** Duplicate measurements of DBH or soil depth should be conducted by independent team members for at least 10% of plots. Differences beyond acceptable thresholds should trigger review and possible re-measurement.
2. **Data Sheet and Entry QA:** Standardized field forms must be reviewed daily. Typed data should be cross-checked with original field records. An error log should be maintained.
3. **Instrument Calibration and Maintenance:** Field and lab instruments (e.g., DBH tapes, GPS, balances) must be calibrated regularly. A log should record date, technician, method, and any adjustments made.
4. **Sample Handling and Lab QA/QC:** Use chain-of-custody protocols. Include blanks, replicates, and controls in lab analyses (e.g., for LOI or elemental analysis). Conduct inter-lab comparisons if possible.
5. **Spatial Data QA:** GPS coordinates should be sub-meter accurate where possible. Plot locations must align with GIS strata. A subset of plots should be revisited for independent verification.
6. **Statistical QA and Sampling Review:** Assess sampling adequacy against the precision target documented in Section A3.5. Distinguish variability among plots, expressed by the coefficient of variation, from uncertainty in the estimated mean. Investigate outliers and document their treatment; do not discard valid observations solely because they are extreme. Reassess sample size using the observed variability.

By integrating robust uncertainty estimation and QA/QC procedures, mangrove blue carbon projects can ensure scientifically credible, verifiable, and transparent reporting—supporting both national GHG inventories and voluntary carbon markets.

A.9 Methodological Levels for Mangrove Carbon Accounting

The Methodological Level system provides guidance for selecting and documenting methods used to estimate mangrove ecosystem extent, carbon stocks, carbon stock changes, and relevant greenhouse gas emissions.

Three methodological levels—Basic, Standard, and Advanced—are distinguished by the specificity, representativeness, calibration, and validation of the underlying data and estimation methods.

The levels describe methodological approaches rather than mandatory sets of instruments. A higher methodological level does not automatically demonstrate greater accuracy or lower uncertainty. Uncertainty shall be assessed independently in accordance with Chapter 6 of the Main Text and Section A.8 of this Annex.

The tables below provide examples of methods corresponding to each level. They do not replace the minimum sampling, measurement, accounting, or monitoring requirements specified elsewhere in this methodology. Different methodological levels may be applied to different carbon pools and accounting components within the same project.

A9.1 Field Data Collection and Laboratory Methods by Measurement Category

The following table describes the general progression of field and laboratory methods used to obtain the inputs required for mangrove carbon accounting.

Measurement category	Level 1 – Basic	Level 2 – Standard	Level 3 – Advanced
Tree diameter and height	Standardized direct measurements of required tree attributes using appropriate field instruments.	Representative, stratified measurements with locally appropriate structural parameters and consistent measurement procedures.	Detailed site-specific structural measurements, potentially including enhanced temporal sampling or additional measurements supporting locally validated biomass models.
Species identification and wood density	Field identification using appropriate guides; published species- or genus-specific wood density values where applicable.	Verified species identification and use of locally or regionally representative wood density data.	Expert-verified identification and locally measured or validated wood density parameters where needed to improve biomass estimation.
Crown and canopy characteristics, where required	Documented field observations or basic measurements appropriate to the selected estimation method.	Standardized crown measurements or canopy-cover assessment using field instruments and representative sampling.	Detailed, calibrated field measurements or appropriately validated spatial techniques for estimating canopy or crown characteristics.

Measurement category	Level 1 – Basic	Level 2 – Standard	Level 3 – Advanced
Biomass sample handling and carbon content	Standardized collection and dry-mass determination where samples are collected; applicable published carbon fractions may be used where permitted.	Representative subsampling and laboratory analysis, including locally appropriate biomass carbon fractions.	Replicated, quality-controlled laboratory analysis and site-specific carbon fractions where these materially improve the estimate.
SOC core collection and depth characterization	Soil coring to the required depth using equipment appropriate to the substrate; depth intervals and sampling information recorded in accordance with Section A.4.3.	Representative cores across strata, with appropriate replication, depth segmentation, and documentation of soil characteristics.	Enhanced replication and vertical characterization, including deeper or higher-resolution cores where warranted by soil conditions and accounting objectives.
SOC bulk density and organic carbon concentration	Site-measured dry bulk density and organic carbon concentration estimated through an appropriate laboratory method, using a justified published conversion factor where applicable.	Representative site measurements, supported by locally or regionally calibrated analytical procedures and appropriate replication.	Detailed, replicated site-specific measurements, supported by validated laboratory analysis and enhanced vertical characterization where warranted.
Litter, where included	Standardized collection and dry-mass determination, with applicable published conversion factors.	Representative quadrat sampling and locally appropriate carbon-content determination.	Enhanced sampling and site-specific analysis, including temporal replication where relevant.
Dead wood, where included	Field measurements of dimensions and decay condition, supported by applicable published density or conversion factors.	Standardized volume and decay assessment using locally representative density parameters.	Detailed, site-calibrated volume or density estimation, with repeated assessment where relevant.
Sediment Accretion and Surface Elevation Measurements, where relevant	Appropriate published sediment-accumulation information or basic site observations,	Site-based measurements using marker horizons, surface elevation tables, or	Replicated or longer-term measurements, potentially supplemented by radiometric dating or

Measurement category	Level 1 – Basic	Level 2 – Standard	Level 3 – Advanced
	subject to justification of applicability.	other suitable methods.	other validated techniques where appropriate.
GHG emissions, where relevant	Applicable conservative emission factors for comparable environmental conditions.	Locally or regionally representative emission factors, supported by appropriate site information or targeted measurements.	Site-specific flux measurements and validated estimation methods with temporal replication sufficient to characterize relevant variability.

All soil-core measurements shall comply with the applicable sample-handling, depth-characterization, and compaction-correction procedures in Section A.4.3, regardless of methodological level.

The methodological level of an accounting estimate shall be determined from the collective suitability and quality of its underlying data and estimation procedures; the use of an individual measurement technique associated with a higher level does not automatically determine the level of the resulting estimate.

A9.2 Methodological Levels for Carbon Accounting Estimates

The following tables describe how data and measurement approaches may be used to estimate mangrove carbon stocks, carbon stock changes, and relevant GHG emissions.

Methodological levels shall be assigned to individual accounting components, rather than treating the entire project as having a single level.

a. Carbon Stock Estimation

Accounting Component	Level 1 – Basic	Level 2 – Standard	Level 3 – Advanced
Ecosystem Area / Extent	Existing ecosystem distribution maps or available spatial datasets, supported by appropriate field	Locally or regionally developed ecosystem maps with systematic field validation, consistent	Detailed, site-specific ecosystem maps supported by rigorous field validation,

Accounting Component	Level 1 – Basic	Level 2 – Standard	Level 3 – Advanced
	confirmation and documented limitations.	delineation, and suitable spatial resolution.	documented classification accuracy, and appropriate assessment of spatial uncertainty.
Aboveground Biomass (AGB)	Field-measured tree attributes combined with applicable published or generalized allometric equations and carbon fractions.	Representative field measurements combined with species- or region-specific equations and locally appropriate parameters.	Detailed site-specific measurements and locally validated estimation models, potentially supported by additional structural or spatial data where appropriate.
Belowground Biomass (BGB)	Published root-to-shoot ratios or generalized belowground biomass equations appropriate to the mangrove type.	Species- or region-specific root-to-shoot ratios or belowground biomass equations supported by representative field data.	Direct root measurements or locally calibrated and validated belowground biomass models where feasible and justified.
Soil Organic Carbon (SOC)	SOC estimation using site-measured soil depth and bulk density, with organic carbon concentration determined using an applicable laboratory method and justified conversion factors.	SOC estimation using representative, stratified soil measurements and locally appropriate or calibrated carbon-concentration estimates.	Detailed site-specific SOC estimation using replicated, vertically resolved measurements and validated analytical procedures.
Litter and Dead Wood, where included	Field measurements combined with appropriate published carbon fractions, density values, or conversion factors.	Representative field measurements using locally appropriate parameters and standardized laboratory procedures.	Detailed, site-specific measurements or validated estimation models where justified by the contribution of these pools.

b. Carbon Stock Change and GHG Estimation

Accounting approach / component	Level 1 – Basic	Level 2 – Standard	Level 3 – Advanced
Stock-Difference Method	Comparison of carbon stock estimates at two comparable time points, supported by measured changes in the relevant accounting inputs and appropriately justified published parameters.	Repeated, representative measurements using locally appropriate parameters and consistent sampling and estimation methods.	Detailed repeated measurements, supported by site-specific calibration, validation, and enhanced characterization of spatial or temporal variability.
Gain-Loss Method	Estimation using applicable published rates or factors for carbon gains and losses, supported by relevant project activity and spatial data.	Locally representative measurements or parameters for the principal carbon gain and loss processes, with published factors used where appropriately justified.	Detailed site-specific estimation of relevant gains and losses, supported by validated models or direct measurements and appropriate temporal characterization.
GHG Emissions, where applicable	Estimation using appropriate published or conservative emission factors.	Estimation using locally representative factors, site observations, or targeted measurements.	Site-specific emission measurements or validated models, with appropriate characterization of temporal and environmental variability.

A.10 Monitoring

Monitoring is where project proponents systematically collect, manage, and analyze data to quantify changes in carbon stocks and greenhouse gas (GHG) emissions within the project boundary over time. For mangrove blue carbon projects, monitoring serves to:

- Ensure that emission reductions and carbon sequestration are real, measurable, and verifiable.

- Track the condition and extent of mangrove ecosystems and associated carbon pools.
- Detect deviations from the baseline scenario and confirm that project activities are implemented as planned.
- Provide the basis for ex-post crediting under relevant certification schemes.

A10.1 Monitoring Plan

The monitoring plan shall document the methodological level assigned to each relevant accounting component, including the data sources, estimation methods, and validation procedures supporting its assignment.

This shall include:

- Parameters to be Measured – All included carbon pools (aboveground biomass, belowground biomass, soil organic carbon, dead wood, litter where significant) and applicable non-CO₂ GHG emissions required for project accounting.
- Frequency of Measurement – Follow the parameter-specific monitoring schedule in this annex. Verification is an independent review process and does not determine field measurement frequency.
- Field and Remote Sensing Methods – Consistent with Sections A.4–A.7, ensuring that methods remain consistent between monitoring events.
- Strata and Plot Management – Permanent plots should be maintained where possible to reduce variance and improve temporal comparability.
- Data Management – Procedures for QA/QC, uncertainty estimation, and data archiving.

A10.2 Monitoring Schedule

Monitoring intervals for each carbon pool are based on their expected rate of change, measurement feasibility, and contribution to total carbon stock.

Table 2: Minimum monitoring frequency by carbon pool

Carbon Pool / Parameter	Minimum Frequency	Notes
Aboveground Biomass (AGB)	Every 5 years	Permanent plots preferred; align with biomass peak season
Belowground Biomass (BGB)	Every 5 years	Derived from AGB or measured directly if species-specific equations updated
Soil Organic Carbon (SOC)	Every 10 years (5 years in early restoration)	Consistent coring depth and methods

Carbon Pool / Parameter	Minimum Frequency	Notes
Dead Wood and Litter (if significant)	Every 5 years	Use line-intersect and subplot methods
Sediment Accretion (RSET–MH)	Annually or seasonally	For sequestration rate estimation
Hydrological Parameters	Continuous or seasonal	Especially where linked to CH ₄ /N ₂ O
Non-CO ₂ GHG emissions (where applicable)	According to the applicable estimation method and monitoring plan	Quantify material emissions using measurements or justified applicable factors; document exclusions under main Section 10.4.

Assess relevant GHG emissions in both the baseline and project scenarios. A source shall not be excluded merely because the project does not claim a flux benefit. Apply the exclusion provisions of main Section 10.4 and document their justification.

A10.3 Parameters and Data Collection

Monitoring must include:

- Biophysical parameters: DBH, tree height, wood density, species composition, soil depth, bulk density, %C_{org}, decay classes.
- Environmental parameters: Water table depth, salinity, tidal regime, disturbance history.
- Geospatial parameters: Area per stratum (A_{i,t}), coordinates of plots, spatial extent of mangrove cover from remote sensing.

Supporting parameters must be collected to ensure robust interpretation of carbon data and to enable cross-checking with remote sensing analyses.

Table 3: Region-Specific Monitoring Parameters for Mangrove Ecosystems

Parameter	Carbon Pool / Component	Unit	Measurement / Analytical Method	Field / Lab Equipment	Notes
DBH (Diameter at Breast Height)	Aboveground biomass – trees/saplings	cm	Measure at 1.3 m above ground or above prop roots per A.4.1	DBH tape, calipers, tree tags, paint	Tag and mark POM for repeatability

Parameter	Carbon Pool / Component	Unit	Measurement / Analytical Method	Field / Lab Equipment	Notes
Tree height (H)	Aboveground biomass – trees	m	Clinometer, laser rangefinder, or height pole	Clinometer, laser rangefinder, telescopic pole	Required if using height-based allometry
Species identification	Above- & belowground biomass	–	Field ID with guides, photographs for verification	Field guide, GPS camera	Supports species-specific allometry
Wood density (ρ)	AGB/BGB	g cm^{-3}	Core extraction and oven drying	Increment borer, balance, oven	Use published values if available
Seedling density	Regeneration AGB	individuals m^{-2}	Count in microplots	Quadrat frames, tally sheets	For carbon stock & regeneration tracking
Pneumatophore density	Belowground biomass proxy	count m^{-2}	Count in fixed-size microplots	Quadrat frames	Use conversion factors or site-specific biomass models
Bulk density (BD)	Soil organic carbon	g cm^{-3}	Oven dry to constant weight, calculate volume	Soil corer, balance, oven, calipers	Keep core diameter & depth consistent
% Organic carbon (%C_{org})	Soil organic carbon	% dry mass	CHN elemental analysis or LOI	Elemental analyzer, muffle furnace, desiccator	Remove carbonates before CHN analysis
Soil depth to refusal	Soil organic carbon	cm	Probe or corer to refusal	Soil depth probe, auger	Needed for total stock calculation
Decay class	Dead wood	Class A–C	Visual assessment per A.4.4	Field sheets, reference photos	Used to account for decomposition condition in standing dead-tree biomass assessment and as a condition

Parameter	Carbon Pool / Component	Unit	Measurement / Analytical Method	Field / Lab Equipment	Notes
					indicator for dead wood.
Dead wood volume	Dead wood	m ³	Line-intersect or direct measurement	Measuring tape, calipers	Convert volume to biomass using the applicable dead-wood density.
Litter mass	Litter pool	g m ⁻²	Collect, weigh, oven-dry	Quadrats, balance, oven	Inclusion or exclusion follows main Sections 4.3.3 and 10.4.
Sediment accretion rate	Soil carbon sequestration	mm yr ⁻¹	RSET–Marker Horizon	RSET device, feldspar/sand, quadrats	Combine with BD and Corg for CAR
Carbon burial rate (historical)	Soil carbon sequestration	g C m ⁻² yr ⁻¹	²¹⁰ Pb dating	Vibracorer, alpha spectrometer	Captures decadal–centennial trends
Water table depth	Supporting parameter (CH ₄ /N ₂ O)	cm below surface	Pressure transducer or staff gauge	Water level loggers, staff gauge	Relevant for non-CO ₂ emissions
Salinity	Supporting parameter (CH ₄ /N ₂ O)	PSU	Multiparameter probe	Conductivity/salinity meter	Relevant for methane suppression assessment
Project boundary & stratum area (Ai,t)	All	ha	GIS analysis of RS data	GIS software, high-res imagery	Update for disturbance/restoration
Non-CO₂ GHG emissions (where applicable)	CH ₄ , N ₂ O	mg m ⁻² hr ⁻¹	Static chambers, gas chromatography	Static chambers, gas vials, GC	Use direct measurements or justified applicable factors; document exclusions under main Section 10.4.

A10.4 Tools and Methods

Field methods shall follow those in Sections A.3–A.7 of this Annex.

Remote sensing data may be used to:

- Detect land cover change and validate project boundary stability.
- Support stratification updates.
- Identify disturbances such as clearing, erosion, or storm damage.

Data sources may include Sentinel-2, Landsat, UAV imagery, and other regionally available high-resolution datasets.

A10.5 Quality Assurance / Quality Control (QA/QC) and Uncertainty Assessment

Projects shall implement QA/QC procedures to minimize measurement error and bias:

- Field crew training and calibration before each monitoring campaign.
- Standardized data sheets and metadata forms.
- Cross-checking of 10% of plots by independent observers.
- Laboratory sample replication ($\geq 10\%$ of samples).
- Documentation of any method changes between monitoring events, with justification.

Estimate uncertainty for each included pool and the project total in accordance with Section A8 and main Chapter 6. Where sampling precision does not meet the adopted target, review the sampling design and increase sampling where necessary. Any uncertainty deduction shall follow the applicable certification requirements.

A10.6 Reporting templates

These templates support consistent reporting of mangrove monitoring results under this annex and the main methodology. Complete the applicable fields for each reporting period, retain the supporting field, laboratory, spatial and calculation records, and cross-reference them using unique identifiers. Expand rows as needed. Enter “not applicable” with a reason where a field does not apply; distinguish zero, not measured and missing data. The templates do not replace the project design document, approved monitoring plan or underlying calculation files.

Report quantities with their units, measurement dates and spatial and depth boundaries. Use carbon fractions as decimals (for example, 0.02), while organic-carbon percentages are entered as

percentage values (for example, 2 for 2%). Keep carbon stocks, stock changes and GHG balances distinct. Report uncertainty under main Chapter 6 and use the applicable monitoring schedule; these templates introduce no new default factors or monitoring frequencies.

For projects covering more than one ecosystem, identify the contribution of each annex and consolidate shared sources, leakage and project-level results once. Annualized rates are not additional amounts to be added to reporting-period totals.

Template R1: Project and reporting period

Field	Entry
Project name and identifier	
Country, locality and proponent	
Report identifier, version and preparation date	
Reporting period start and end; duration and annualization basis	
Project start date and activity type; implementation completed during this period	
Applicable methodology and annex versions; monitoring-plan identifier	
Project boundary/map version and total area (ha)	
Baseline scenario and additionality documentation reference; changes since previous report	
Accounting approach by pool or component; methodological level and justification reference	
Previous report reference; changes in methods, boundaries or strata and comparability assessment	
Prepared by; internal reviewer; organization, roles and dates	

Template R2: Strata and spatial changes

One row per stratum. Areas must refer to dated, non-overlapping accounting units. Attach the boundary-change reconciliation where strata were split, merged, gained or lost; do not interpret an area change alone as a carbon-stock change.

Stratum ID	Habitat and management condition	Start area (ha)	End area (ha)	Map dates and versions	Area uncertainty reference	Change and evidence reference

Template R3: Monitoring implementation

One row per parameter or sampling component. Attach the sampling design and environmental observations required to interpret the measurements. Report the number of independent sampling units, distinguishing subsamples and repeat observations.

Parameter or pool and stratum	Method and SOP version	Planned frequency and dates	Actual dates and independent sample count	Responsible team	Deviation and corrective action	Data and QA record reference

Template R4: Biomass carbon stock summary

Repeat for each stratum, measurement date and scenario where biomass stocks are used. Supporting field records must preserve the original measurements and conversions; this table reports the resulting stratum estimates.

Field	Entry
Stratum ID; measurement date; scenario or observed inventory	
Independent plot/quadrat/core count and sampling-design reference	
Stratum area (ha) and spatial-record reference	

Pool	Mean dry biomass (Mg/ha)	Carbon fraction or parameter reference	Mean carbon stock (Mg C/ha)	Stratum carbon stock (Mg C)	Calculation and uncertainty reference
Aboveground living biomass					
Belowground living biomass					
Dead wood, where included					
Litter, where included					

Retain the following in the linked field and laboratory records:

- Permanent plot and tree identifiers; coordinates and reference system; plot/subplot area (m²); measurement date and team.

- Species, live/dead status, DBH (cm), measurement height or alternative diameter point, and height (m) where required by the model.
- Allometric equation identifier, parameter units, applicability range, wood density (g/cm³) where used, and source or measurement reference.
- Belowground estimation method, sampled depth where relevant, and root-to-shoot relationship only where applicable and justified.
- For included dead wood and litter: sampling method and dimensions, decay class where relevant, measured mass or volume, density/conversion factors and sample identifiers.

If carbon fractions differ among samples or species, calculate carbon before aggregation and cite the detailed calculation rather than imposing a single mean fraction. Do not add a subtotal to its component pools.

Template R5: Soil carbon and depth basis

Use one core record for each sampled core and one layer row for each analysed interval. The layer table may be supplied as a linked electronic schedule.

Field	Entry
Stratum, plot and core identifiers; date and coordinates	
Corer internal diameter (cm); penetration and recovered lengths (cm)	
Actual assessed depth (cm); refusal or other limitation	
Compression assessment and any correction; interval and volume basis	
Living-root/rhizome removal; retained dead material and pool allocation	
Laboratory/SOP reference; carbon analysis method; carbonate treatment and dry-mass basis	
Core photographs, chain-of-custody and sample register references	

Sample ID	Assessed depth interval (cm)	Dry bulk density (g/cm ³)	Organic carbon (%)	Layer stock (Mg C/ha)	Laboratory and calculation reference

Stratum ID	Common reporting depth (cm)	Independent core count	Mean SOC (Mg C/ha)	Stratum SOC (Mg C)	Uncertainty and calculation reference

Normally report measured stocks within 0–100 cm. Report shallower stocks at their actual depth and deeper stocks separately. Do not extrapolate a shallow stock to 1 m by a depth ratio. Identify any estimated unmeasured intervals separately and document their justification and uncertainty. Use a consistent depth basis for comparisons; document interval-boundary treatment and design-consistent averaging of cores.

Template R6: Carbon stock change

Complete the panel applicable to each pool and scenario. Where methods differ among pools, document their boundaries and demonstrate that the same change is not counted twice. These are carbon results, not project GHG benefits.

Stock difference panel

Interval start and end: _____. Elapsed years: _____. Scenario: _____.
Area/depth comparability and boundary-change reconciliation: _____.

Stratum and pool	Start stock (Mg C)	End stock (Mg C)	Change (Mg C)	Annualized change (Mg C/yr)	Calculation reference

Gain and loss panel

Interval start and end: _____. Elapsed years: _____. Scenario: _____.
Rate integration and spatial scaling reference: _____.

Stratum and pool	Gains over interval (Mg C)	Losses over interval (Mg C)	Net change (Mg C)	Annualized net change (Mg C/yr)	Calculation and overlap check reference

Apply area once when converting per-hectare quantities to stratum totals. Preserve negative net changes. Where accretion or radiometric burial informs gains, record method, assessed dates/depths, rate units, carbon concentration convention, and whether the estimate is gross accumulation or net burial. Keep surface-elevation change distinct from accretion. Do not add historical interval rates as simultaneous annual gains or subtract losses already represented by a net burial estimate.

Template R7: GHG accounting summary

Complete the component ledger separately for baseline and project scenarios, using the same reporting period and compatible accounting boundaries. Link annual schedules where required. Include each term once, documenting overlap between stock changes, respiration and other measured fluxes.

Scenario and year/period	Source or removal and spatial scope	Gas or carbon basis	Input amount and unit	Conversion or GWP reference	Signed result (tCO ₂ e)	Calculation and overlap-check reference

Use positive values for emissions and negative values for removals in scenario balances. A stock increase converted to a removal therefore enters with the opposite sign to the positive stock-change result. Document use of 44/12 for carbon-to-CO₂ conversion and applicable 100-year GWPs for CH₄/N₂O. Identify whether measurements are expressed as gas mass or carbon/nitrogen mass and document any necessary conversion before applying GWP.

Accounting item	Reporting-period result (tCO ₂ e)	Annualized result (tCO ₂ e/yr)	Calculation reference
Net baseline GHG balance			
Net project GHG balance			
Baseline minus project before leakage			
Leakage deduction			
Net GHG benefit after leakage			

Calculate net GHG benefit as baseline balance minus project balance minus leakage under main Section 9.6. Leakage deductions shall not be negative. Do not add avoided emissions again where already represented in the baseline–project difference. For a multi-ecosystem project, provide the consolidated project table once and cross-reference each annex contribution.

Field	Entry
Applicable uncertainty/conservativeness adjustment, amount, unit and rule reference, or not applicable	
Non-permanence or reversal treatment and evidence reference, where applicable	
Relationship between reported benefit, any adjusted result and the consolidated project report	

Apply a deduction or buffer only where required by the applicable certification framework; identify its rule and calculation separately. Report any applicable adjustment separately and identify its rule and calculation. These reported estimates are not an issuance or certification decision.

Template R8: Uncertainty statement

Repeat this record for each material estimate and the consolidated result. Where an uncertainty budget is lengthy, attach it and retain its identifier here.

Field	Entry
Estimate identifier, scenario, period and spatial/pool/depth scope	
Point estimate and unit	
Standard error or other uncertainty measure; identify its type and unit	
Confidence level and interval limits, where applicable	
Relative precision measure and definition; adopted target and source, where applicable	
Sampling design, independent sample count and estimation/propagation method	
Included sources: sampling, model, carbon fraction, laboratory, area and other material sources	
Shared errors/covariance and area weighting; treatment of omitted sources	
Calculation reference, limitations and any additional sampling or corrective action	

Distinguish standard error, coefficient of variation and confidence-interval width. Do not treat them as interchangeable or combine incompatible uncertainty measures.

Template R9: Parameters and exclusions

Parameter register — one row per applied factor, model or conversion, including carbon fractions, allometry, LOI calibration, emission factors and GWP values as applicable.

Parameter ID and use	Value or equation and unit	Source with page/table/version	Site/species/depth applicability	Uncertainty or calibration evidence	Calculation reference

Exclusion register — record included, excluded and zero-valued terms distinctly. Assess project-level cumulative exclusions under main Section 10.4.

Pool, GHG or leakage term	Included/excluded/zero	Basis and applicable provision	Estimated omitted contribution (tCO ₂ e)	Evidence reference	Reassessment trigger

Field	Entry
Project-level cumulative de minimis assessment reference and period	
Combined contribution of terms tested (tCO ₂ e) and estimation basis	
Net GHG benefit before leakage used as denominator (tCO ₂ e)	
Calculated percentage, conclusion and treatment of non-positive/undefined denominator	
Evidence that exclusions do not overstate benefits; treatment of any adverse pool change	

Do not use a pool's share of standing carbon stock as the significance denominator. A non-positive or undefined denominator does not demonstrate that an exclusion passes. A source is not excluded merely because no flux benefit is claimed.

Template R10: QA review and risk follow-up

Ebb sf wfx sf dpæ

Dataset or calculation ID	Check performed and coverage	Finding or limitation	Correction and status	Reviewer and date	Evidence/version reference

Cover field completeness, calibration, sample traceability, laboratory checks, data-entry review, units, formulas, spatial/depth comparability and double-counting checks as applicable. Retain original records and document corrections rather than silently replacing them.

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Risk/event ID and date	Affected stratum and extent (ha)	Observed or potential effect	Action, owner and due date	Accounting/reversal assessment reference	Follow-up status and evidence

Field	Entry
Raw field/laboratory records, photographs and spatial archive location	
Calculation files, SOP versions, parameter sources and uncertainty files	
Outstanding issues and their effect on the reported results	
Prepared by and date; internal technical review by and date	
Independent verification status and statement reference, if available	

Retain records under the main methodology's retention requirements. Internal review does not constitute independent verification.

A.11 Regional Parameter Tables

A11.1 Mangrove Species in the East and Southeast Asia Region

Table 4: Sample Mangrove Species and their Wood densities

SPECIES	n	AVERAGE WOOD DENSITY (TONNES/m ³) (1 g/cm ³ = 1 Mg/m ³)	STANDARD ERROR
<i>Avicennia germinans</i>	5	0.72	0.04
<i>Avicennia marina</i>	6	0.62	0.06
<i>Avicennia officinalis</i>	3	0.63	0.02
<i>Bruguiera gymnorhiza</i>	8	0.81	0.07
<i>Ceriops decandra</i>	2	0.87	0.1
<i>Ceriops tagal</i>	7	0.85	0.04
<i>Excoecaria agallocha</i>	7	0.41	0.02
<i>Heritiera fomes</i>	3	0.86	0.14
<i>Heritiera littoralis</i>	6	0.84	0.05
<i>Laguncularia racemosa</i>	3	0.6	0.01
<i>Rhizophora apiculata</i>	4	0.87	0.06
<i>Rhizophora mangle</i>	7	0.87	0.02
<i>Rhizophora mucronata</i>	9	0.83	0.05
<i>Sonneratia alba</i>	6	0.47	0.12
<i>Sonneratia apetala</i>	2	0.5	0.01
<i>Xylocarpus granatum</i>	7	0.61	0.04

(Saenger 2002; Komiyama et al. 2005; Donato et al. 2012; World Agroforestry Center 2001 on Howard et al. 2014)

A11.2 Allometric Equations

Table 5. General and Species-Specific Allometric Equations (DBH Only) for Estimating AGB in Mangroves

Tree Species	Equation B = Biomass (kg) DBH (cm), H (m), ρ (g/cm ³)	R ²	RSE	DBH Range (cm)	Source
General	$B = 0.251 \cdot \rho \cdot (\text{DBH})^{2.46}$	0.979		< 45.0	Komiyama et al., 2005 ¹
<i>Aegiceras corniculatum</i>	$B = 0.780778 \cdot \text{DBH} - 0.325215$	0.896		4.0-6.5	He Qinfei et al., 2017
<i>Bruguiera gymnorrhiza</i>	$B = 0.186 \cdot \text{DBH}^{2.31}$	0.99		< 25.0	Clough & Scott, 1989; Liao Baowen et al., 1991
<i>Kandelia candel</i>	$B = 0.01016 \cdot (\text{DBH})^{2.454}$	-		< 2.0	Lunstrum and Chen, 2014
<i>Avicennia marina</i>	$B = 1.5066 \cdot \text{DBH}^{1.595}$	0.94		< 35.0	Comley & McGuinness, 2005

Table 6. General and Species-Specific Allometric Equations (DBH with Height) for Estimating AGB in Mangroves

Tree Species	Equation DBH (cm), H (m), ρ (g/cm ³)	R ²	RSE	DBH Range (cm)	Height (m)	Source
General	$\text{AGB} = 0.0673 \cdot (\rho \cdot D^2 \cdot H)^{0.976}$		0.357			Chave et al., 2014 ^{2,3}
<i>Aegiceras corniculatum</i>	$B = 0.02039 \cdot (D^{0.2} H)^{0.83749}$	0.987		< 20.0	< 2.0	Ning Shijiang et al., 1996
<i>Kandelia candel</i>	$B = 0.03999 \cdot (\text{DBH}^2 H)^{1.053}$	0.83		4.0-13.0	2.0-5.5	Tam et al., 1995
<i>Avicennia marina</i>	$B = 0.116291 \cdot (D_0^2 H) - 0.348657$	0.999		< 2.0	-	He Qinfei et al., 2017

D_0 applies to smaller vegetation like shrub, bush, and young plants; DBH applies to grown trees

¹ <https://core.ac.uk/download/pdf/59148776.pdf>

² <https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcb.12629>

³ <https://winrock.org/wp-content/uploads/2018/08/Winrock-AllometricEquationGuidance-2016.pdf>

Table 7. Allometric Equations (DBH Only) for Estimating BGB in Mangroves

Tree Species	Equation DBH (cm), H (m), ρ (g/cm ³)	R ²	RSE	DBH Range (cm)	Source
General Mangrove	$B = 0.199 \cdot (\rho)^{0.899} \cdot (\text{DBH})^{2.22}$	0.949		-	Komiyama et al., 2005
<i>Bruguiera gymnorhiza</i>	$B = 0.4697 \cdot (\text{DBH})^{1.5543}$	0.99		< 25.0	Clough & Scott, 1989; Liao Baowen et al., 1991
<i>Kandelia candel</i>	$B = 0.007649 \cdot (\text{DBH})^{2.064}$	-		< 2.0	Lunstrum and Chen, 2014

Table 8. Species-Specific Allometric Equations (DBH with Height) for Estimating BGB in Mangroves

Tree Species	Equation DBH (cm), H (m), ρ (g/cm ³)	R ²	RSE	DBH Range (cm)	Height (m)	Source
<i>Kandelia candel</i>	$B = 0.02972 \cdot (\text{DBH}^2 \cdot H)^{0.990}$	0.95		4.0-13.0	2.0-5.5	Tam et al., 1995

A11.3 Root-to-Shoot Ratios

Mangrove Species	Root-to-Shoot Ratio	R ²	RSE	Source
General (average)	0.26			Cairns et al. (1997) ⁴
General (range)	0.05 - 0.70			Cairns et al. (1997)
General (mangroves)	0.21 - 1.55			Komiyama et al. (2008)
<i>Avicennia marina</i>	0.38			Njana et al. (2015) ⁵
<i>Sonneratia alba</i>	1.29			Njana et al. (2015)
<i>Rhizophora mucronata</i>	0.62			Njana et al. (2015)

⁴ <https://www.scielo.br/j/aabc/a/QnBQqmQJQJ8YJCMPmJr3qGj/?format=pdf&lang=en>

⁵ <https://annforsci.biomedcentral.com/articles/10.1007/s13595-015-0524-3>

Mangrove Species	Root-to-Shoot Ratio	R ²	RSE	Source
<i>Rhizophora apiculata</i>	0.4			Indonesian National Standard 7724:2011 ⁶
<i>General Malaysian Mangroves</i>	2.65			Jackson et al. (2024) ⁷

A.12 Templates and Examples

A12.1 Sample Uncertainty Computations

a. Single Tree: Uncertainty in AGB

Estimate uncertainty in individual-tree aboveground biomass using the selected allometric model's documented error structure. Distinguish absolute errors, relative errors and errors expressed on a logarithmic scale; apply the corresponding conversion or uncertainty procedure.

Express the resulting biomass estimate and its standard error in the same units:

$$\text{Reported AGB} = \text{Estimated AGB} \pm \text{SE}_{\text{AGB}}$$

This expression reports one standard error, not a confidence interval.

b. Apply Uncertainty to Carbon Fraction

Carbon stock is calculated by multiplying the AGB by the carbon fraction (typically 0.47 or 0.49 depending on the source). The uncertainty in carbon stock is obtained by applying the carbon fraction to both the AGB and its uncertainty:

$$\text{Carbon Stock} = \text{AGB} \times \text{Carbon Fraction}$$

$$\text{Uncertainty in Carbon Stock} = \text{Uncertainty in AGB} \times \text{Carbon Fraction}$$

⁶ https://www.bio-conferences.org/articles/bioconf/pdf/2024/06/bioconf_icfaes2024_02008.pdf

⁷ https://www.pure.ed.ac.uk/ws/portalfiles/portal/82516720/82516624._Jackson._AAM.pdf

These expressions treat the carbon fraction as fixed and scale the biomass standard error into a carbon-stock standard error. They do not include uncertainty in the carbon fraction. Include that uncertainty separately where applicable, accounting for any dependence.

c. Plot-Level Carbon Stock and Uncertainty

Sum the individual-tree carbon stocks to obtain plot carbon stock. Where individual-tree carbon-stock errors are independent, combine their standard errors using:

$$SE_{Plot,C} = \sqrt{\sum_{j=1}^n SE_{C,j}^2}$$

Here, $SE_{C,j}$ is the standard error of the carbon-stock estimate for tree j . All terms shall use the same carbon-mass unit.

Where estimates share an allometric model or carbon fraction, account for correlated errors using covariance or an uncertainty model that represents the dependence, following main Chapter 6.

d. Carbon Stock per Hectare

Divide the plot carbon stock and its associated uncertainty by the sampled plot area in hectares:

$$Carbon\ Stock\ per\ Hectare\ (Mg\ C/ha) = \frac{Plot\ Carbon\ Stock\ (Mg\ C)}{Area\ of\ Plot\ (ha)}$$

$$Uncertainty\ per\ Hectare\ (Mg\ C/ha) = \frac{Uncertainty\ in\ Plot\ Carbon\ Stock\ (Mg\ C)}{Area\ of\ Plot\ (ha)}$$

These calculations express plot carbon stock and its uncertainty on a per-hectare basis, assuming plot area is fixed. If plot carbon stock is recorded in kg C, divide by 1,000 to convert it to Mg C before applying these equations.

e. Average Carbon Stock per Hectare Across All Plots

Within each stratum, calculate mean plot carbon density and its sampling standard error. For simple random sampling of independent plots:

$$SEM = \frac{\text{Standard Deviation of Carbon Stocks across plots}}{\sqrt{\text{Number of plots}}}$$

Reported Mean Carbon Stock per Hectare = Mean Carbon Stock per Hectare $\pm$ SEM

Both the mean and SEM are expressed in Mg C/ha. This SEM represents sampling uncertainty in the stratum mean. Incorporate other uncertainty components following main Chapter 6, avoiding double counting of components already represented.

f. Scale Up to Total Area

Calculate the carbon total separately for each stratum by multiplying its mean carbon density by its area:

$$\text{Stratum Carbon Stock (Mg C)} = \text{Mean Carbon Stock (Mg C/ha)} \times \text{Stratum Area (ha)}$$

$$\text{Sampling SE of Stratum Carbon Stock (Mg C)} = \text{SEM (Mg C/ha)} \times \text{Stratum Area (ha)}$$

These expressions treat stratum area as fixed. Account for area uncertainty where applicable, then aggregate stratum totals and propagate their uncertainties following main Chapter 6.

g. Combine Uncertainties Using Error Propagation

Within each stratum, combine the standard errors of mean carbon stock per hectare and stratum area using error propagation. If these errors are independent, the relative standard uncertainty of the stratum carbon total is calculated as follows:

$$\text{Total Relative Uncertainty} = \sqrt{\left(\frac{SE_{\text{Carbon Stock per ha}}}{\text{Carbon Stock per ha}}\right)^2 + \left(\frac{SE_{\text{Area}}}{\text{Area}}\right)^2}$$

This combines uncertainties from carbon stock and area estimates, following the error propagation formula for independent variables.

h. Final Report of Carbon Stock and Uncertainty

Convert relative standard uncertainty to absolute standard uncertainty:

$$\text{Absolute Standard Uncertainty (Mg C)} = \text{Estimated Carbon Stock (Mg C)} \times \text{Relative Standard Uncertainty}$$

If relative uncertainty is expressed as a percentage, divide it by 100 before multiplication. Aggregate stratum estimates and their uncertainties following main Chapter 6 before reporting the project total.

$$\text{Reported Project Carbon Stock} = \text{Estimated Project Carbon Stock} \pm \text{Absolute Standard Uncertainty}$$

Label this result as one standard uncertainty. Where a confidence interval is required, calculate and report it at the stated confidence level using the appropriate statistical method.

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