PV CLIMATE TOOL

PT006

Tool for Ground Truth Sampling

Version 1.0

29 Sep 2025

Developed by:

Acorn [Planting a better future with smallholder farmers | Acorn Rabobank]

Approved by:

AENOR Confía [Company certification. Everything you need to know | AENOR]

Contents

1 Summary ... 3
2 Sources ... 3
3 Definitions ... 3
4 Applicability Conditions ... 4
5 Procedures ... 4
5.1 Procedure for selection of location of ground truth data ... 4
5.1.1 Data sources and requirements ... 4
5.1.2 Method ... 5
5.2 Standard operating procedure for ground truth data collection ... 7
5.2.1 Define sample plot ... 7
5.2.2 Define subplots within the sample plot ... 7
5.2.3 Measurement and inventory of AGB per subplot ... 8
Primary crops/woody vegetation ... 10
Vegetation > 1.3 m woody/tree-like ... 10
Vegetation < 1.3 m woody/tree-like ... 10
Non woody vegetation ... 11
5.3 Translate tree measurement into Aboveground Biomass ... 11
5.3.1 Pre-processing subplot level data ... 11
5.3.2 Pre-processing tree data ... 11
5.3.3 AGB calculation ... 14
Multi-stemmed trees and shrubs ... 14
Stem basal diameter ... 15
AGB calculation shrubs ... 15
AGB calculation trees ... 16
AGB calculation systematically sampled groups ... 16
5.3.4 Wood density selection ... 17
5.3.5 Project Area AGB ... 18
6 Parameters ... 19
7 Reference ... 27
8 Appendix ... 29
8.1 Measuring tree height without a tool ... 29
8.2 Measuring DBH ... 30

1 Summary

The approach to select representative *ground truth data* collection locations, per *ecoregion* (*stratum*) is described in this *Tool*. In addition, the standard operating procedure (SOP) for *ground truth data* collection and a method to transform it for use as input for *biomass* modelling are provided. *Ground truth data* must be utilized to develop, train, and validate the *biomass* model described in *Methodology* **PM002** and *Module* **PU006**, as well as to estimate the *pre-project tree biomass* on a *Project Area Level*. The *ground truth data* must be also used to determine the contributions of *pre-project tree biomass* described in *Methodology* **PM002** and *Module* **PU007**.

The data must be subdivided per *ecoregion* to incorporate differences in growth rates of tree species due to environmental conditions.

To assure the full range of *biomass* within the *stratum* is covered, both environmental conditions and an indication of *pre-project tree biomass* must be considered to determine a representative selection of ground truth locations within an *ecoregion*. Features related to environmental conditions include altitude, slope, rainfall, temperature, and soil type. A remote sensing-based vegetation index (NDVI or RVI) of the year prior to data collection must be used as an indicator of existing *biomass*. These parameters will be calculated and categorized for all *Project Areas* within the *Project* with at least 1 ha. GPS will be used to outline the *Project Area* of a *Project Participant*. A *sample plot* is defined as a 1ha area used for *ground truth data* collection. If there aren't enough *Project Areas* with a minimum size of 1 ha, neighbouring *Project Areas* can be combined to create an area of more than 1 ha which can be utilized for *sample plot*. A *subplot* is defined as a 25x25 m area within a *sample plot*.

2 Sources

This *Tool* supports the following *Modules*:

- **PU006** Module for Model Development, Calibration, Validation and Application of Remote Sensing-based Models of Aboveground Biomass in Smallholder Agroforestry v1.0
- **PU007** Module for Performing Adaptive Pre-project Woody Biomass Baseline for Small-scale Agroforestry v1.0

3 Definitions

All terms in this document follow the PV Climate Glossary and **PM002**, with the addition of the following definitions:

Categories

Represent distinct environmental conditions, combining numerical *categories* (equal pixel value ranges) and grouped categorical parameters. They guide the stratified selection of *sample plots* for *ground truth data* collection for balanced model calibration.

Stratum
A group into which members of a population/*Project Area(s)* are divided into stratified sampling based on specific characteristics. In this *Tool* an *ecoregion* is considered a *stratum*. Where necessary, further stratification can be done through, for example, a variety of *pre-project tree biomass* or *Project* activities.

Subplot
A 25x25 m area within a *sample plot*.

4 Applicability Conditions

The procedures described in this *Tool* are globally applicable, as the implemented features are available for every *ecoregion* and are applied to a specific *Project*. For this *Tool*, the applicability conditions of the *Methodology* **PM002** should be met.

5 Procedures

5.1 Procedure for selection of location of ground truth data

5.1.1 Data sources and requirements

The data sources needed for the selection of representative *sample plots* for *ground truth data* collection are summarized in Table 1. *Required data sources for the selection of representative sample plots – including all data parameters, sources, and resolution.*

Table 1. Required data sources for the selection of representative sample plots – including all data parameters, sources, and resolution.

Parameter	Example Source*	Minimum required resolution	Data Type
Soil type	SoilGrids dataset, soil type parameter (Poggio, L, et al., 2021; SoilGrids, 2025)	250 m	Categorical (nominal; with 30 categories)
Elevation	Copernicus DEM (COP-DEM, 2022) (ESA)	30 m	Numerical (continuous)
Precipitation	CHIRPS (Hijmans et al., 2005)	5 km Yearly Sum	Numerical (continuous)
Temperature	ERA5 sensor via ECMWF datasets (Muñoz Sabater, J., 2019, Simmons, A., et al	11 km Yearly minimum and maximum	Numerical (continuous)

	2020; Hersbach, H., et al, 2020)		
Temperature anomalies	ERA5 (Muñoz Sabater, J., 2019)	11 km (5-year count in months)	Numerical (discrete)
Land cover	ESA (WorldCover, 2021; Zanaga et al., 2021)	30 m	Categorical (nominal; with 11 *categories*)
NDVI or RVI	Red and Near-Infrared bands of Sentinel-2 or similar multispectral sensor (Rouse et al., 1973; Sentinel Hub, 2023; Drusch et al., 2012); Sentinel-1 or similar sensor (Hu X., et al., 2024)	10 m for Sentinel 2 derived product; Sentinel 1 GRD of approx. 20 × 22 m, pixel spacing of 10 m	Numerical (continuous)

**The source might differ from the one listed in the table. If an alternative source is needed, the resolution requirement should be met.*

The following criteria need to be met for a location to be suitable for *ground truth data* collection:

- The measured area must be at least 1 ha of land (comprising of 1 or multiple adjacent *agroforestry Project Areas*).
- All parameters listed in Table 1 should be available for download. If the listed source is not available, alternative, globally available, open-source data with similar or better resolution should be used (preferably a published paper or data report).
- All parameters should be in raster format.
- All parameters should be in the same coordinate systems.
- All parameters should be in the same grid resolution. The parameter with the highest available resolution is used as the standard to follow for the lower-resolution parameters. E.g. if the highest resolution is 10x10 m, a lower-resolution parameter of 30x30 m is up sampled to 10x10 m.
- All *Project Areas* that belong to the *Project* must be defined.
- The number of desired ground truth locations should be pre-defined based on criteria described in **PM002** Section 6.1.

5.1.2 Method

1. Pre-process data.
    a. Rasterize vector-based data sets to facilitate processing performance.
    b. Transform data to the same coordinate reference system to make the data spatially compatible.
    c. Resample the different datasets to the same grid to align pixels in the various raster data.

d. If satellite indices are not directly available to download (i.e. Sentinel Hub), image processing has to be implemented, following procedures explained in **PU006**.
e. *Sample plots* that belong to the *Project* must be used for *ground truth data* collection. If the *Project Area* is smaller than 1 ha, adjacent *Project Areas* can be combined to cover a 1 ha area to create a *sample plot*.
f. Exclude *sample plots* smaller than 1ha with no adjacent *Project Areas*.
g. Extract all data per *sample plot.*

2. Categorise data.
   a. The goal of this step is to select *Project Areas*, which represent the variability of the *ecoregion*, that can be used for *ground truth data* binned into five equally sized *categories* based on the pixel distribution across all *Project Areas*. First, all pixel values from the *Project Area* will be collected and sorted by variable value. Then, the sorted pixel values will be divided into five equal parts, ensuring each *category* contains the same number of pixels. Similarly, the categorical parameters will also be binned into 5 *categories*.
   All possible combinations between the numerical and categorical parameters will be assessed. Since *ecoregions* have similar temperature, elevation, and soil type less than 100 combinations are often possible.
   To select *sample plots* for *ground truth data,* all available *Project Area*s from the *Project* with a size of 1 ha or larger will be allocated to each *category* based on the numerical and categorical values they contain. For model calibration, each *category* should contain the same number of *Project Areas* selected for *ground truth data*.
   If *categories* are insufficiently represented, *Project Area*s within the underrepresented *categories* will be prioritised for collection if the *Project* expands with *Project Area*s in the underrepresented *categories*. If the number of *Project Areas* available is higher than the desired number of ground truth locations, a stratified systematic sampling approach will be used to make the most appropriate selection. Stratified systematic sampling is a sampling method that first divides a population into distinct subgroups (strata) based on shared characteristics, and then selects samples from each *stratum* at regular intervals (systematically) to ensure balanced and representative coverage.
   b. Decrease the number of *categories* for the parameter with the lowest coefficient of variation (CV)-score.
   The higher the CV, the greater the dispersion (spread in values) of that parameter. Therefore, the aim is to have a higher number of *categories* for parameters with the largest variation. If a parameter has a low variation (e.g., the temperature varies little between all *Project Areas*), the parameter will be categorized in fewer *categories* to reduce the number of unique combinations of *categories*.
   c. The previous step must be repeated until the unique combination count is below or equal to the desired ground truth location sample size. For each iteration over parameters, the next parameter in the CV-ranking (2nd smallest variation, 3rd smallest variation, etc.) will be selected for decreasing the number of *categories*.

After the *sample plots* for *ground truth data* have been selected following the steps above, the collection of *ground truth data* in these *sample plots* can start. This is described in the segment below.

5.2 Standard operating procedure for ground truth data collection

Starting with definitions and explanations:

Figure 1. Graphical representation of a Smallholder's land property, incl. relevant definitions and explanations

1. Land-property: entire land-property of the *Smallholder* (excluding roads, houses, timber lots, etc.).
2. *Project Area* should exclude roads, buildings etc. when such infrastructure is located at the edge of a *Project Area* and when it is feasible for *ground truth measurement* to exclude. *Project Areas* are defined by polygons.
3. *Sample plot*: An area of a maximum of 1 ha within a *Project Area*, where *ground truth measurements* take place.
4. *Subplot*: a 25x25 m *area* within a *sample plot*.

5.2.1 Define sample plot

The first step is to determine a *sample plot* on the *Project Area* of the *Smallholder*. Ideally, a *sample plot* is a 1 ha square of 100 m by 100 m. If that is not possible within the assigned *Project Participant's Project Area*, a different rectangular shape covering 1 ha is allowed.

After establishing the polygon, the outlines of the *sample plot* can be pinpointed by GPS coordinates. At least 1 GPS coordinate is required per corner of the *sample plot*. Placing demarcation poles and/or flags at these corner points ensures that trees are measured within the right area.

5.2.2 Define subplots within the sample plot

Each *sample plot* will be divided into 16 *subplots*, square-shaped of 25x25 m, using measuring tape and a compass. Each *subplot* will be numbered and added to a simple sketch that lays out the entire *sample plot*. An example is shown in Figure 2 below. Corner points will be demarcated using poles and/or flags at the corner points. At every corner of each *subplot* at least one coordinate pair with an accuracy of maximum 5 m needs to be recorded.

Per *sample plot* the following data should be collected:

- GPS coordinates (preferably in DD (Decimal Degree) format)
- Name of collector
- Name of *Project Area/Smallholder*
- Date, location

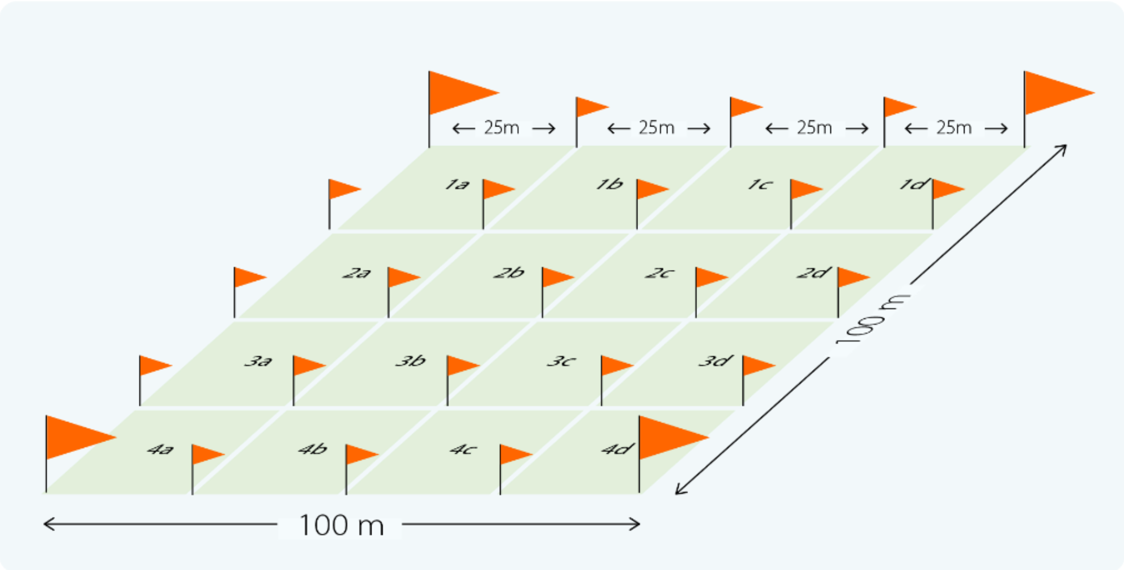

Figure 2. Example of a sample plot

5.2.3 Measurement and inventory of AGB per subplot

After the *subplots* are demarcated, measurements will be taken to estimate *AGB* for woody plants higher than 1.3 meters for the purpose of model calibration, validation and determination of other adjustment factors. Non-woody and woody plants lower than 1.3 meters are inventoried, but not used in the *AGB* calculation.

If a plant is located on the *Project Area* border, the plant will be measured if most of its stem is inside the *subplot*. If most of the plant's stem is outside of the *subplot*, it will not be measured.

The measurement methods depend on the vegetation characteristics. During data collection a distinction is made for woody vegetation between tree and *shrub* growth forms by the number of stems (Zizka et al., 2014) and their diameter at breast height values (DBH). For woody vegetation up to 6 stems, or stems with a diameter at breast height (DBH) larger than 10 cm, the diameters of all stems must be measured at breast height. For woody vegetation with more than 6 stems, and with stems with a DBH smaller than 10 cm, the basal stem diameter ($D10$) is measured at 10 cm height.

Grouping is accepted for plants with a DBH smaller than 10 cm or primary woody vegetation (see Table 3). Grouped sampling will be done by systematically sampling the population, based on the population size. The average of the sample measurements will be used to calculate *biomass* per group (see Equation 8). Grouped sampling is only allowed when the group meets the following criteria:

- The population consists of at least 6 individual plants;
- The population consists of a single species;
- The population shares the same planting year, which should be known for all plants;
- Deviations from the group such as unhealthy or dying trees should be measured separately.

The systematic sampling approach depends on the population size, therefore the total number of plants in the group should be determined first. The selection of the “n” sample is indicated in Table 2, depending on the sample size, moving systematically through the *Project Area* in a zig-zag manner: start at the corner of a *subplot*, then move horizontally across the first row, sampling at regular intervals. After reaching the end of the first row, move up to the next row and go in the opposite direction. Repeat the pattern until the required samples are taken. For trees that are not planted in rows, start at the corner of a *subplot*, then move in a zig-zag path across the area, regardless of the tree positions. At each step, select the nearest trees to the path at regular intervals. Repeat the pattern until the required samples are taken. At least three plants (samples) must be taken from the population.

Table 2. Systemically sample approach for population size.

Min. size	Max. size	Every “n” sample
6	12	2nd
12	20	4th
20	30	6th
30	-	10th

The measurements taken will depend on the vegetation type. See Table 3 for examples per vegetation type:

Table 3. Examples per vegetation type.

Vegetation type	Example species
Primary woody vegetation	Coffee, cacao, tea, fruit trees (if primary crop)
Vegetation > 1.3 m & woody/tree-like	Ceder, Inga, Baobab, fruit trees (non-primary crops), palms
Vegetation < 1.3 m & woody/tree-like	Saplings or seedlings of woody species

Non-woody vegetation	Maize, rice, sorghum, sugarcane, grass

Primary crops/woody vegetation

Identify the primary woody, tree-like crop above 1.3 m height. If there are multiple primary crops (e.g. mixed coffee and cocoa plantation with shade trees in between) make separate groups per crop (i.e. one for coffee and one for cocoa).

Per group record for each sample:

- Scientific species name (if not available, use genus or common name)
- Planting year
- Plant count
- Of every systematically chosen sample of the group:
  - Height (see Section 8.1);
  - Pruning height (when pruned);
  - Total number of stems at diameter measurement height;
  - DBH (see Section 8.2) or D10.

Vegetation > 1.3 m woody/tree-like

For every individual plant or sample record:

- Scientific species name (if not available, use genus or common name);
- Planting year;
- Height (see Section 8.1);
- Pruning height (when pruned);
- Total number of stems at diameter measurement height;
- DBH (see Section 8.2) or D10;
- Tree location (at least one coordinate pair).

Vegetation < 1.3 m woody/tree-like

Identify all woody, tree-like plants lower than 1.3 m. These plants can be grouped based on identical species and planting year. Otherwise, they must be measured as different groups. Per group the following characteristics must be measured.

Per group record:

- Scientific species name (if not available, use genus or common name);
- Planting year;
- Plant count;
- Of every systematically chosen sample of the group:
  - Height (see Section 8.1);
  - Pruning height (when pruned);
  - Total number of stems.

Non woody vegetation

Non-*woody AGB* should be inventoried based on % cover or plant count per *subplot*. Non-*woody AGB* is required to make an inventory of the amount of vegetation but will not be considered for model calibration or carbon calculations.

Non-woody plants can be grouped based on identical species and planting year. Otherwise, they must be measured as different groups. Per group the following characteristics must be measured for the smallest, median and largest plant within the group:

- Scientific species name (if not available, use genus or common name);
- Coverage percentage or plant count;
- Height, if applicable (see Section 8.1).

5.3 Translate tree measurement into Aboveground Biomass

The field data will be combined into individual plant level and *subplot* level datasets for further processing. Both datasets will be pre-processed to remove or correct invalid data. After pre-processing both datasets, *biomass* will be calculated per *shrub*, tree, and systematically sampled group and aggregated on a *subplot* level (See Equation 1). If the acceptance criteria for a *subplot* from both the individual plant level dataset and *subplot* level dataset are met, the *subplot* will be used for further modelling.

$$AGB_{subplot} = \sum AGB_{shrub} \in subplot + \sum AGB_{plant} \in subplot + \sum AGB_{group} \in subplot$$

Equation 1

Where:

$AGB_{subplot}$	= Total *Aboveground Biomass* of one *subplot* (kg)
AGB_{shrub}	= *Aboveground Biomass* of a separately measured *shrub* (kg)
AGB_{plant}	= *Aboveground Biomass* of a separately measured tree-like plant (kg)
AGB_{group}	= *Aboveground Biomass* of a systematically sampled group (kg)
$subplot$	= Selected *subplot* to calculate *biomass*

5.3.1 Pre-processing subplot level data

The collected *subplots* must be checked for geometrical and locational accuracy including projection, protrusion, size, number of vertices, and duplicate *subplot*-IDs.

5.3.2 Pre-processing tree data

The data will be pre-processed to translate species names, enforce data quality checks, standardise value formats, format qualitative variables, and detect and correct abnormal data.

Species names must be corrected for grammar, spelling, and other typographical errors. The collected species names will be translated to scientific species names. If no translation can be found for a species name, the translated species name will be set to “UNKNOWN_species”.

Values above the threshold for DBH and height values will be flagged. The standard threshold for DBH is 1590 cm, which is the DBH of a baobab tree (*Adansonia digitata*), currently the largest *agroforestry* tree in the world (South African Government, 2022). The threshold for height is 70 m, since trees higher than 70 m are rare (Tng et al., 2012). The threshold is selected to reflect the highest trees in typical tropical *agroforestry* systems. If the *Tool* is used for different systems, the thresholds have to be adjusted to reflect the average height and DBH of typical tree species derived from peer reviewed literature sources.

Where possible, species-specific thresholds for DBH and height are researched from peer-reviewed literature. If one of the parameters of height or DBH exceeds the threshold, an appropriate allometric equation is researched, based on the same conditions listed in the first paragraph of Section 5.3.3, or derived from the collected data, to calculate the correct value according to the correct parameter. If both height and DBH exceed the threshold, the average species-specific DBH is used to calculate the height. The species-specific value for DBH is derived from the collected data by the *Project*. Of these variables, DBH measurements and wood density values are considered the most reliable inputs. Trees, which are subject to coppicing practice, must be measured following established procedures in peer reviewed literature. As such, additional tree characteristics, such as coppicing height, have to be recorded.

The standard method of correcting woody plant dimensions is done by following the DBH-height allometric formula from Chave et al., (2014), see Equation 2a. The derived equation to calculate height from the DBH and environmental stress factor is Equation 2b. To calculate DBH from height and the environmental stress factor, Equation 2c is further simplified into Equation 2d. The environmental stress factor was calculated by Chave et al., (2014) with Equation 3 and processed into a global gridded layer. The environmental stress factor is retrieved based on the location of the *subplot* of the trees.

$$\ln(H) = 0.893 - E + 0.760 * \ln(DBH) - 0.0340 * \ln(DBH)^2$$

Equation 2a

Where:

H = Tree height (m)

DBH = Diameter at breast height (cm) for single-stemmed trees/*shrubs* OR estimated diameter at breast height (DBH_{est}) for multi-stemmed trees/*shrubs* (cm)

E = Environmental stress variable based on geographical location

$$H = e^{(0.893 - E + 0.760*\ln(DBH) - 0.0340*\ln(DBH)^2)}$$

Equation 2b

Where:

H = Tree height (m)

DBH = Diameter at breast height (cm) for single-stemmed trees/*shrubs* OR estimated diameter at breast height (DBH_{est}) for multi-stemmed trees/*shrubs* (cm)

E = Environmental stress variable based on geographical location

The equation to solve DBH is derived from Equation 2a by using the quadratic formula (Equation 2c).

$$\ln(DBH) = e^{\frac{-0.760 \pm \sqrt{(0.760)^2 - 4*(-0.0340)*(0.893 - E - \ln(H))}}{2*(-0.340)}}$$

Equation 2c

Where:

H = Tree height (m)

DBH = Diameter at breast height (cm) for single-stemmed trees/*shrubs* OR estimated diameter at breast height (DBH_{est}) for multi-stemmed trees/*shrubs* (cm)

E = Environmental stress variable based on geographical location

Equation 2c, due to its quadratic form, yields two possible solutions. However, only one provides meaningful values, accurately representing the allometric relationship between DBH, height, and the environmental stress factor. Equation 2d is the result of the application of exponentiation and multiplication to derive an equation to estimate DBH based on height and the environmental stress factor.

$$DBH = e^{\frac{-0.760 + \sqrt{0.5776 + 0.136*(0.893 - E - \ln(H))}}{-0.068}}$$

Equation 2d

Where:

H	= Tree height (m)
DBH	= Diameter at breast height (cm) for single-stemmed trees/*shrubs* OR estimated diameter at breast height (DBH_{est}) for multi-stemmed trees/*shrubs* (cm)
E	= Environmental stress variable based on geographical location

$$E = (0.178 * TS - 0.938 * CWD - 6.61 * PS) * 10^{-3}$$

Equation 3

Where:

E	= Environmental stress variable based on geographical location
TS	= Temperature Seasonality
CWD	= Climate Water Deficit
PS	= Precipitation Seasonality

5.3.3 AGB calculation

After pre-processing, *AGB* will be calculated for each measured *shrub*, woody/tree-like plant and systematically sample group, with an appropriate allometric *biomass* equation. The rank-order method of the Quality Assessment of REDD+ Carbon Credit Projects by Berkeley Carbon Trading Project will be used (Haya et al., 2023) to select the most appropriate *biomass* equation.

The applicability range of each equation is also considered. If a measurement falls outside the range for which the equation was developed:

- the maximum applicable range of the equation will be used;
- an alternative equation with a suitable applicability range will be selected;
- or the mathematical form of the equation will be assessed to determine whether extrapolation is appropriate.

Multi-stemmed trees and shrubs

For multi-stemmed trees or *shrubs*, a stem diameter equivalent is calculated with Equation 4 from the mean diameter of the measured stems at the stem measurement height (Monteiro et al, 2016; Magarik et al., 2020; Shukor et al., 1993; Chojnacky & Milton, 2008; Chojnacky, 1994). If mean stem diameter is greater than 40 cm, the mean value of the stem diameter is used to avoid overestimation (Monteiro et al., 2016).

$$DH_{est} = \sqrt{\sum_{i=1}^{n_{stems}} DH_{mean}^2}$$

Equation 4

Where:

DH_{est}	= Estimated stem diameter at a certain stem height (cm)
DH_{mean}	= Mean stem diameter of all stems of the tree or *shrub* at a certain stem height (cm)
n_{stems}	= Total number of stems of the tree or *shrub* at stem height used for diameter measurements

Stem basal diameter

Stem basal diameter is calculated from the DBH, if stem basal diameter is an input for the most appropriate *biomass* equation. Stem basal diameter is defined as the stem diameter at 10 cm stem height (Conti et al., 2019; Paul et al., 2016). To convert the DBH to the basal stem diameter, the formula by Paul et al. (2016) is used. See Equation 5 below.

$$D10_{est} = 1.488 + 1.195 * DBH_{(est)}$$

Equation 5

Where:

$D10_{est}$	= Estimated basal stem diameter at 10 cm stem height (cm)
$DBH_{(est)}$	= Diameter at breast height (DBH) for single-stemmed trees/*shrubs* OR estimated diameter at breast height (DBH_{est}) for multi-stemmed trees/*shrubs* (cm)

AGB calculation shrubs

Shrubs are defined as species which are woody non-climbing plants without a clearly defined main stem, branching off below stem height of 1.30 meters, with a maximum species height smaller than 5 meters (Zanaga et al., 2022; Conti et al., 2019). The definition of *shrub* is assigned on a per species basis, based on literature or plant databases (e.g. POWO, 2025), by looking at its dominant habit and maximum attainable height.

Based on the recommendation of Conti et al. (2019), the standard generic equation for *shrubs* worldwide is derived from Paul et al. (2016). See Equation 6 below.

$$AGB_{shrub} = e^{(2.474*\ln(D10_{(est)}))-2.575} * 1.0787$$

Equation 6

Where:

AGB_{shrub} = *Aboveground Biomass* of a *shrub* (kg)

$D10_{(est)}$ = (Estimated) Basal diameter at 10 cm height (cm)

AGB calculation trees

The allometric equation to estimate *Aboveground Biomass* of tropical trees by Chave et al. (2014) will be used as the default *biomass* equation for trees, if no more appropriate *biomass* equation is available. This equation calculates *AGB* for pantropical tree species based on DBH, height and wood density. See Equation 7 below.

$$AGB_{plant} = 0.0673 * (\rho * DBH^2 * H)^{0.976}$$

Equation 7

Where:

AGB_{plant} = *Aboveground Biomass* of a separately measured tree-like plant (kg)

ρ = Wood density (g/cm^3)

DBH = Diameter at breast height (cm) for single-stemmed trees/*shrubs* OR estimated diameter at breast height (DBH_{est}) for multi-stemmed trees/*shrubs* (cm)

H = Tree height (m)

AGB calculation systematically sampled groups

Aboveground Biomass of a sampled group is calculated by first averaging all measurements. *Biomass* for one sample is then determined with an appropriate *biomass* equation using the average of the required parameters from the measurements. Total *biomass* for the sampled group is calculated by multiplying the *biomass* for one sample with the total population of the sampled group. See Equation 8 below.

$$AGB_{group} = f_{biomass}([\overline{param_{measured}}], [\Delta \ldots]) * n_{group}$$

Equation 8

Where:

AGB_{group}	= Total *Aboveground Biomass* of one sample group (kg)
$f_{biomass([\Delta \ldots])}$.	= *Biomass* equation appropriate for measured species (kg)
$\overline{param_{measured}}$	= Parameter representing a required parameter for the selected *biomass* equation, based on the average of the measurements from the samples in the systematically sampled group
n_{group}	= Total number of plants in the whole group (n)

5.3.4 Wood density selection

Depending on the *biomass* equation, a wood density value may be needed as a parameter. The wood density values will be first extracted from the ICRAF wood density database (Orwa et al., 2010). Wood density should be selected based on the region and species or genus level. If no wood density can be found for a plant on a genus level, a literature search should be done.

If multiple values are found on the same species, genus or regional level, the average wood density value will be used for the *AGB* calculations.

If no information is available for the wood density values of a woody species within the ICRAF database and literature, the average wood density value of all woody species within the data collection will be used for the *AGB* calculations. The order of selection can be found in Figure 3 below.

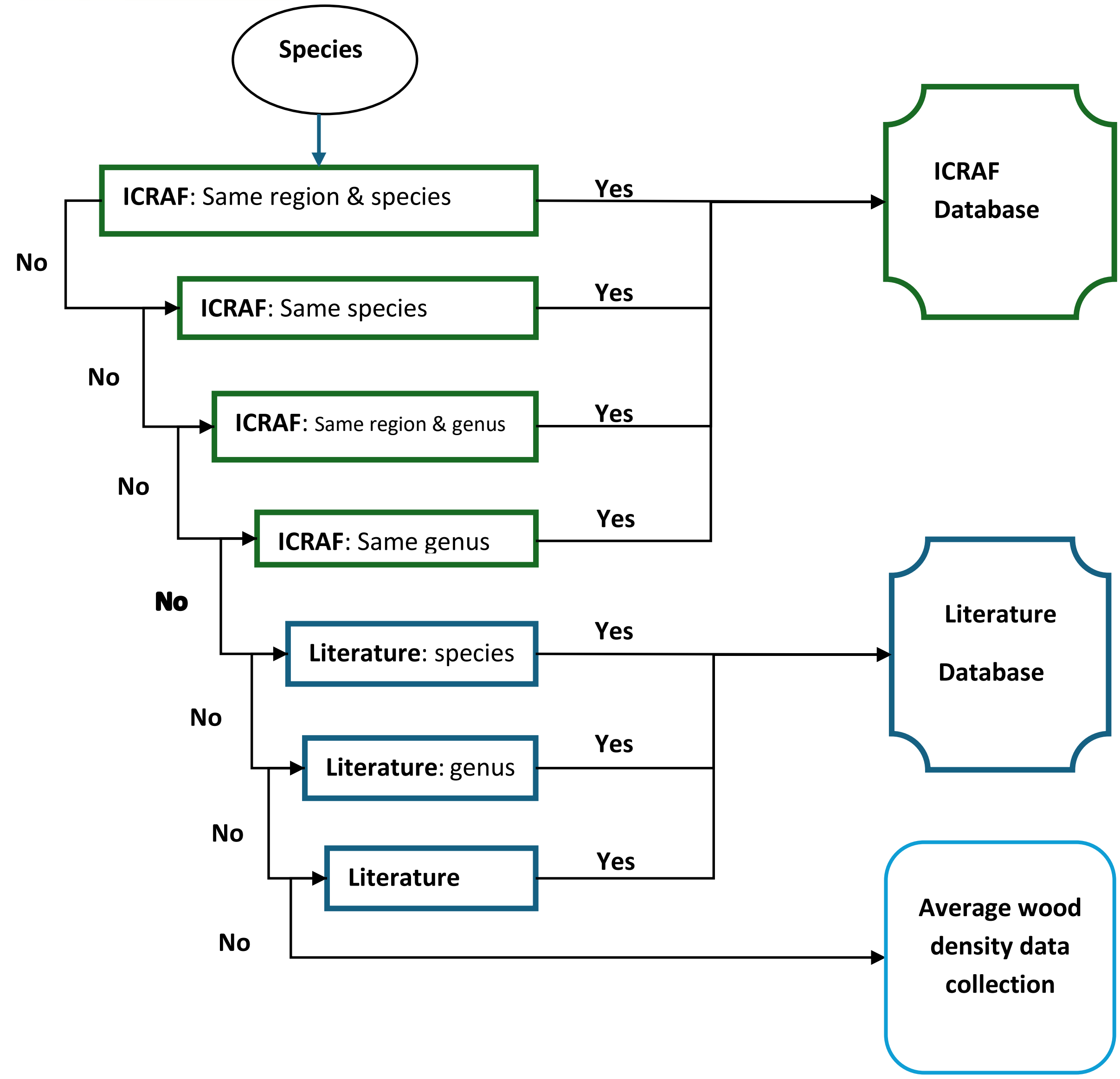

Figure 3. Wood density selection process

5.3.5 *Project Area AGB*

After the *AGB* calculations, *AGB* density per *subplot* must be calculated by dividing the total *subplot AGB* with the *subplot* area. *AGB* density per *subplot* must be calculated with Equation 9. The output of Equation 9 is used for quality assessment and verification as part of a field audit.

$$AGBsubplot\ per\ hectare = \frac{AGBsubplot}{1000} \cdot \left(\frac{10000}{area_{subplot}}\right)$$

Equation 9

Where:

$AGBsubplot\ per\ hectare$ = *Aboveground Biomass* density *subplot* (tonne/ha)

$AGBsubplot$	= *Aboveground Biomass* per *subplot* (kg)
$area_{subplot}$	= *subplot* area (m^2)

Total *AGB* per *sample plot i* must be calculated by adding all *subplot biomass* values and dividing by the sum of the *subplot* areas. *AGB* density per *sample plot* must be calculated with Equation 10.

$$AGBplot_i = \frac{\sum \frac{AGB_{subplot}}{1000} \in plot}{\sum \frac{area_{subplot}}{10000} \in plot}$$

Equation 10

Where:

$AGBplot_i$	= *Aboveground Biomass* density within *sample plot i* (tonne/ha)
$AGBsubplot$	= *Aboveground Biomass subplot* (kg)
$area_{subplot}$	= *subplot* area (m^2)
$plot$	= selected *sample plot* to calculate *biomass* density

6 Parameters

Data/Parameter	AGB_{plant}
Units	Kg
Description	*Aboveground Biomass* of one plant
Equations	Equation 1 and Equation 7
Source	*Ground truth data* and appropriate allometric models (e.g. Chave et al. (2014))
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	The parameter is derived following Chave et al. (2014) from *ground truth measurements* of individual trees.
Purpose of Data	It is the *AGB* per plant, which then contributes to the *AGB* per *sample plot*.
Comments	N/A

Data/Parameter	$area_{subplot}$

Units	m^2
Description	*subplot* area (m^2)
Equations	Equation 9 and Equation 10
Source	*Ground truth data*
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	The *subplot* is selected to minimize potential error during data collection.
Purpose of Data	*Subplot* size is needed to determine *AGB* density of a *subplot*
Comments	N/A

Data/Parameter	CWD
Units	mm / Month
Description	Climate Water Deficit
Equations	Equation 3
Source	Chave et al. (2014); WorldClim (https://worldclim.org/)
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	The maximum Climatological Water Deficit (CWD) is computed by summing the difference between monthly rainfall Pi and monthly evapotranspiration ETi.
Purpose of Data	It is used to calculate the environmental stress factor, which will determine the appropriate allometric value based on the DBH-height allometry from Chave et al. (2014)
Comments	N/A

Data/Parameter	DBH; DBH_{est}
Units	Centimetres (cm)
Description	Diameter breast height (DBH) for single-stemmed trees/*shrubs;* Estimated diameter at breast height (DBH_{est}) for multi-stemmed trees/*shrubs*
Equations	Equation 2a, Equation 2b, Equation 2c, Equation 2d, Equation 5, and Equation 7
Source	*Ground truth data* collection; Equation 4
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	Common practice for calculating *AGB* from *ground truth data*
Purpose of Data	Collected to calculate *AGB* value from *ground truth data*

Comments	N/A

Data/Parameter	DH_{mean}
Units	cm
Description	Mean diameter of all stems of a tree or *shrub* at a certain stem height.
Equations	Equation 4
Source	*Ground truth data* and Monteiro et al. (2016); Magarik et al. (2020); Shukor et al. (1993); Chojnacky & Milton, (2008); Chojnacky, (1994).
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	This parameter is used to estimate a diameter at a certain stem height, to be able to use *biomass* equations for multi-stemmed trees. As described by Monteiro et al. (2016); Magarik et al. (2020); Shukor et al. (1993); Chojnacky & Milton, (2008); Chojnacky, (1994).
Purpose of Data	It is the diameter input to estimate a diameter at stem height for a multi-stemmed tree or *shrub*.
Comments	N/A

Data/Parameter	Elevation
Units	Meters (m)
Description	The Digital Elevation Model that represents the surface of the Earth globally
Equations	Not applicable
Source	Copernicus DEM (COP-DEM, 2022) (Digital Elevation Model)
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	Altitude is an important indicator of *biomass* growth. The parameter is important as it is a proxy for *biomass* growth, water availability and *biomass* type. In the context it is used as a parameter that can enhance the stratification for sampling.
Purpose of Data	The parameter is used as one of the inputs for selection of representative sample of *ground truth data*
Comments	N/A

Data/Parameter	$f_{biomass([\Delta \ldots])}$
Units	kg

Description	Represents the appropriate *biomass* equation for selected species within the sample group, with optional averaged parameters, depending on the required input of the *biomass* equation
Equations	Equation 8
Source	*Ground truth data*
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	This parameter is used to calculate the *biomass* of one sample of the systematically sampled group, based on the average measurement samples.
Purpose of Data	Input to calculate the total *Aboveground Biomass* per sampled group
Comments	N/A

Data/Parameter	H
Units	Meter (m)
Description	Tree height
Equations	Equation 2a, Equation 2b, Equation 2c, Equation 2d, and Equation 7
Source	*Ground truth data* collection or calculated with Equation 2b
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	Common practice for calculating *AGB* from *ground truth data*.
Purpose of Data	Collected to calculate *AGB* value from *ground truth data*
Comments	N/A

Data/Parameter	Land cover
Units	No unit
Description	Classifications of land types
Equations	Not applicable
Source	ESA (WorldCover, 2021; Zanaga et al., 2021)
Value	N/A
Justification of choice of data or description of measurement methods and procedures applied	The data represents the land cover variability within the *Project Area*.
Purpose of Data	The data is used to identify different landcover *categories* within the *Project Area* that can have impact on *biomass* growth. It is used for representative *ground truth data* selection.

Comments	N/A

Data/Parameter	NDVI
Units	No unit
Description	The normalized difference vegetation index is simple and effective for measuring the density of vegetation. Red and Near-Infrared bands of Sentinel-2 or similar multispectral sensor are used (Rouse et al. (1973); Sentinel Hub (2023); Drusch et al. (2012))
Equations	Not applicable
Source	Rouse et al. (1973); Sentinel Hub (2023); Drusch et al. (2012)
Value	N/A
Justification of choice of data or description of measurement methods and procedures applied	A simple indication of *biomass* is used to cover the full range of *biomass* present in the *Project.* The parameter is chosen over any other possible satellite-derived index, as it is the most commonly used and understood index describing vegetation cover. The data is readily available and can be directly downloaded from Sentinel Hub ensuring repeatability of the results and the method. Alternative indices would require data processing and calculation, which for the purpose of the data, would introduce unnecessary complexity.
Purpose of Data	Select a representative sample of *ground truth data.* In the context it is used as a parameter that can enhance the stratification for sampling.
Comments	N/A

Data/Parameter	n_{group}
Units	No unit
Description	Total number of plants in the whole group (n)
Equations	Equation 8
Source	*Ground truth data*
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	This parameter is used to multiply the *biomass* of one sample of the group to determine the total group *biomass*.
Purpose of Data	Input to calculate the total *Aboveground Biomass* per sampled group
Comments	N/A

Data/Parameter	n_{stems}

Units	cm
Description	Total number of stems at the height of a measured diameter
Equations	Equation 4
Source	*Ground truth data* and Monteiro et al. (2016); Magarik et al. (2020); Shukor et al. (1993); Chojnacky & Milton, (2008); Chojnacky, (1994).
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	This parameter is used to estimate a diameter at a certain stem height, to be able to use *biomass* equations for multi-stemmed trees. As described by Monteiro et al. (2016); Magarik et al. (2020); Shukor et al. (1993); Chojnacky & Milton, (2008); Chojnacky, (1994).
Purpose of Data	It is the stem number input to estimate a diameter at stem height for a multi-stemmed tree or *shrub*.
Comments	N/A

Data/Parameter	$\overline{param_{measured}}$
Units	-
Description	Parameter representing a required parameter for the selected *biomass* equation, based on the average of the measurements from the samples in the systematically sampled group
Equations	Equation 8
Source	*Ground truth data*
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	This parameter is a placeholder and needs to be replaced with the required parameter needed as input for the selected *biomass* equation for the species from the sample group. The parameter is the average of the measurements of the samples of the systematically sampled group.
Purpose of Data	Input to calculate the total *Aboveground Biomass* per sampled group
Comments	N/A

Data/Parameter	Precipitation
Units	Millimetres (mm)
Description	Input to calculate the Precipitation Seasonality (PS)
Equations	Not applicable

Source	Hijmans, R. J. et al. (2005)
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	This dataset was used by the authors Chave et al. as part of the process to determine the CWD and PS variables.
Purpose of Data	Select a representative sample of *ground truth data.* In the context it is used as a parameter that can enhance the stratification for sampling.
Comments	N/A

Data/Parameter	PS
Units	Mm/month
Description	Precipitation Seasonality
Equations	Equation 3
Source	Chave et al. (2014); and the environmental stress factor map created by the authors Chave et al. using WorldClim dataset (https://worldclim.org/)
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	Precipitation Seasonality is the coefficient of variation in monthly rainfall values, or the SD expressed in percent of the mean value.
Purpose of Data	It is used to calculate the environmental stress factor, which will determine the appropriate allometric value based on the DBH-height allometry from Chave et al. (2014)
Comments	N/A

Data/Parameter	RVI
Units	No unit
Description	Ratio Vegetation Index
Equations	Not applicable
Source	Rouse et al. (1973); Sentinel Hub (2023); Drusch et al. (2012)
Value	N/A
Justification of choice of data or description of measurement methods and procedures applied	Indication of vegetation conditions to cover the full range of *biomass* within a *Project*.
Purpose of Data	Select a representative sample of *ground truth data.* In the context it is used as a parameter that can enhance the stratification for sampling.
Comments	N/A

Data/Parameter	Soil type
Units	Soil *categories*

Description	Spatial distribution of soil properties across the globe
Equations	Not applicable
Source	SoilGrids dataset, soil type parameter (Poggio, L, et al. (2021); SoilGrids (2025))
Value	Name
Justification of choice of data or description of measurement methods and procedures applied	Soil type is an important indicator of *biomass* growth. When combined with other data layers, it also determines the type of vegetation that can grow on specific soil types and conditions.
Purpose of Data	Select a representative sample of *ground truth data.* In the context it is used as a parameter that can enhance the stratification for sampling.
Comments	N/A

Data/Parameter	Temperature
Units	Degrees Celsius
Description	Raster image derived from satellite data, with approximate resolution of 30km. Each pixel contains one temperature value in degrees Celsius.
Equations	Not applicable
Source	ERA5, sensor via ECMWF datasets (Muñoz Sabater, J. (2019), Simmons, A. et al (2020); Hersbach, H. et al. (2020))
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	Temperature is an important indicator of *biomass* growth. When combined with other data layers, it also determines the type of vegetation that can grow under specific temperature ranges.
Purpose of Data	Use maximum, minimum and anomalies of the *Project Areas* as features. In the context it is used as a parameter that can enhance the stratification for sampling.
Comments	N/A

Data/Parameter	Temperature anomalies
Units	Degrees Celcius
Description	This parameter
Equations	Not applicable
Source	ERA5 (Muñoz Sabater, J. (2019)); https://ourworldindata.org/grapher/monthly-temperature-anomalies
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	ERA5 is the latest climate reanalysis produced by ECMWF, providing hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of *uncertainty*.
Purpose of Data	The parameter is used to establish anomalies within the *Project Areas* that can impact *biomass* growth.

Comments	N/A

Data/Parameter	TS
Units	Degrees Celsius * 100
Description	Temperature seasonality (TS), is the standard deviation (SD) of the monthly mean temperature over a year, expressed in degrees Celsius multiplied by 100.
Equations	Equation 3
Source	Chave et al. (2014); WorldClim (https://worldclim.org/)
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	Temperature seasonality is a parameter in the calculation of the environmental stress value, as defined by Chave et al. (2014).
Purpose of Data	It is used to calculate the environmental stress factor, which will determine the appropriate allometric value based on the DBH-height allometry from Chave et al. (2014)
Comments	N/A

Data/Parameter	ρ
Units	g/cm^3
Description	Wood density
Equations	Equation 4
Source	ICRAF wood density database (Orwa et al. (2010))
Value	Number
Justification of choice of data or description of measurement methods and procedures applied	It is a parameter that integrates species-specific characteristics for the *AGB* calculation or adjusts the *biomass* equation to be representative of different species
Purpose of Data	Used to calculate *AGB* for pantropical tree species value from *ground truth data*
Comments	N/A

7 Reference

Chave, J., et al., (2014). Improved allometric models to estimate the aboveground biomass of tropical trees, Global Change Biology, 20(10), p. 3177–3190. https://doi.org/10.1111/gcb.12629

Chojnacky, D. C. (1994). Volume equations for new Mexico's pinyon-juniper dryland forests.

Chojnacky, D. C., & Milton, M. (2008). Measuring carbon in shrubs. *Field measurements for forest carbon monitoring: A landscape-scale approach*, 45-72.

Conti, G., Gorne, L. D., Zeballos, S. R., Lipoma, M. L., Gatica, G., Kowaljow, E., ... & Fernandes, P. M. (2019). Developing allometric models to predict the individual aboveground biomass of shrubs worldwide. *Global Ecology and Biogeography*, *28*(7), 961-975.

COP-DEM, (2022). https://doi.org/10.5270/ESA-c5d3d65

Drusch, M., et al., (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. Remote sensing of Environment, 120, p. 25-36 https://doi.org/10.1016/j.rse.2011.11.026

Funk, C., et al., (2015). The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes, Scientific Data, 2(1). https://doi.org/10.1038/sdata.2015.66

Haya, B.K., et al., (2023). Quality assessment of REDD+ carbon credit projects. Berkeley Carbon Trading Project. https://doi.org/10.2139/ssrn.2941317

Hersbach, H., et al., (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049, https://doi.org/10.1002/qj.3803

Hu, X., et al., (2024) Radar vegetation indices for monitoring surface vegetation: Developments, challenges, and trends, Science of The Total Environment, 945.

Magarik, Y. A., Roman, L. A., & Henning, J. G. (2020). How should we measure the DBH of multi-stemmed urban trees?. *Urban Forestry & Urban Greening*, *47*, 126481.

Martin, A.J. (2022). Accuracy and Precision in Urban Forestry Tools for Estimating Total Tree Height. Arboriculture & Urban Forestry (AUF), 48(6), p. 319-332. https://doi.org/10.48044/jauf.2022.024

Monteiro, M. V., Doick, K. J., & Handley, P. (2016). Allometric relationships for urban trees in Great Britain. *Urban Forestry & Urban Greening*, *19*, 223-236.

Muñoz Sabater, J., (2019). ERA5-Land hourly data from 1950 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.e2161bac

Orwa, C. et al., (2010). Agroforestree Database: a tree reference and selection guide version 4.0. World Agroforestry Centre, Kenya Agroforestree database: a tree reference and selection guide version 4.0 - CIFOR-ICRAF Knowledge (Accessed: February 26, 2025)

Paul, K. I., Roxburgh, S. H., Chave, J., England, J. R., Zerihun, A., Specht, A., ... & Sinclair, J. (2016). Testing the generality of above-ground biomass allometry across plant functional types at the continent scale. *Global change biology*, *22*(6), 2106-2124.

Poggio, L. et al., (2021). SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty, Soil, 7(1), p. 217–240. https://doi.org/10.5194/soil-7-217-2021

POWO (2025). "Plants of the World Online. Facilitated by the Royal Botanic Gardens, Kew. Published on the Internet; https://powo.science.kew.org/ Retrieved 20 May 2025."

Rouse, J.W., et al., (1973). Monitoring Vegetation Systems in the Great Plains with ERTS (Earth Resources Technology Satellite). Proceedings of 3rd Earth Resources Technology Satellite Symposium, Greenbelt, 10-14 December, SP-351, 309-317.

Shukor, N. A. A., Awang, K., Venkateswarlu, P., & Senin, A. L. (1993). Three-year performance of Acacia auriculiformis provenances at Serdang, Malaysia. *Pertanika Journal of Tropical Agricultural Science*, *17*, 95-102.

Simmons, A., et al., (2020). Global stratospheric temperature bias and other stratospheric aspects of ERA5 and ERA5.1.European Centre for Medium-Range Weather Forecasts, Global stratospheric temperature bias and other stratospheric aspects of ERA5 and ERA5.1 | ECMWF (Accessed: February 26, 2025)

Tng, D.Y.P., et al., (2012). Giant eucalypts–globally unique fire-adapted rain-forest trees?. New Phytologist, 196(4), 1001-1014. https://doi.org/10.1111/j.1469-8137.2012.04348.x

Zanaga, D., et. al., (2021). European Space Agency WorldCover 10 m 2020 v100. https://doi.org/10.5270/ESA-01

Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., ... & Arino, O. (2022). ESA WorldCover 10 m 2021 v200.

Zizka, A., Govender, N., & Higgins, S. I. (2014). How to tell a shrub from a tree: A life-history perspective from a South African savanna. *Austral Ecology*, *39*(7), 767-778.

8 Appendix

8.1 Measuring tree height without a tool

If there are no tools such as clinometer or hypsometer available to measure the height of the tree, follow these steps:

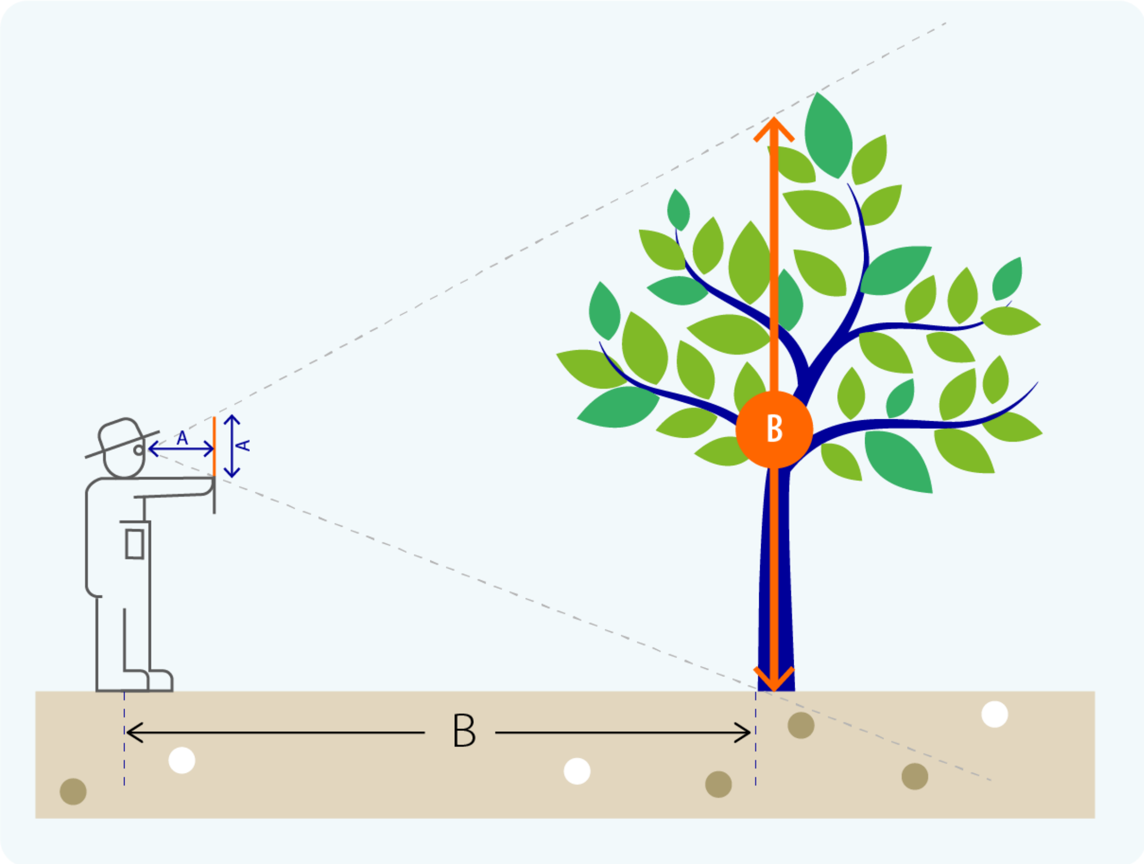

Figure 4. How to measure the height of a tree without a laser measuring tool

1. Measure the horizontal distance from your eye to the hand of your outstretched arm (a).
2. Hold the ruler vertically in front of you. The distance from the top of the ruler to where you hold it must be the same length as the distance from your eye to your hand (a).
3. Walk towards or away from the tree until the tree is visually the same length as the length between the top of the ruler to your hand (a).
4. Mark the location where you are standing and measure the distance from there to the trunk of the tree (b). This distance is the height of the tree (b).

8.2 Measuring DBH

Depending on the measurement materials used, either the circumference or diameter of the tree should be recorded at breast height DBH (1.3 meters) for plants larger than 1.3 meters. Preference is given to measuring stem circumference. Examples of measurement materials and their related stem dimensions used are diameter calliper (DBH), measuring tape (circumference), or diameter tape (DBH). The stem dimension, either DBH or circumference, is noted by the data collector. If circumference is used, it must be converted to diameter by dividing the circumference by π before proceeding with the DBH calculation.

Measuring DBH per tree brings challenges related to different tree shapes and orientations in the field. See Figures 5 below, based on Martin (2022), for guidance on how to measure DBH. Please note these instructions should be merely considered for guidance and may be subject to change if more accurate techniques are found.

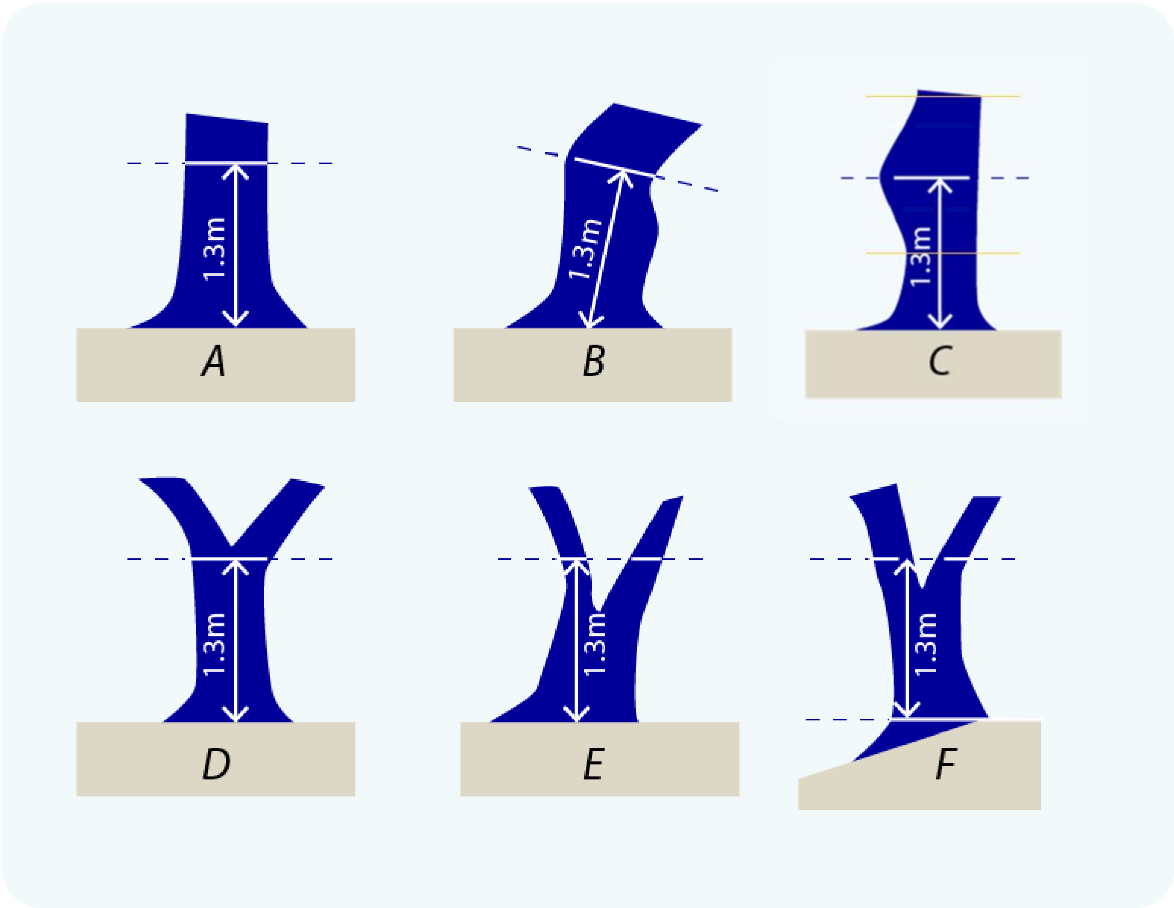

Figure 5. Where to measure DBH on different shapes of trees

a. Normal tree: Wrap the measuring tape horizontally around the tree.
b. Bent tree: Wrap the measuring tape around the tree in the shortest way, which is often not horizontal.
c. Tree with an irregular diameter at 1.3 m: Measure DBH below and above the irregularity and report the average value.
d. Tree forked above 1.3 m: Measure as a normal tree.
e. Tree forked below 1.3 m: Measure DBH of stems and average the values.
    a. If total number of stems is larger than 6, and the DBH of the stems are smaller than 10 cm, measure stem basal diameter(s) at 10 cm stem height (D10). Average D10 for all stems if there are multiple stems at 10 cm stem heigh.
f. Tree located on a hill: Measure at 1.3 m height from the highest point of the soil.