Publication Date:
05/07/2024

Methodology:
M001

Version:
V1.1

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METHODOLOGY

Quantification Methodology for Terrestrial Forest Restoration

SUMMARY

This document details the methodological approach for quantifying GHG removals from terrestrial forest restoration activities. To guarantee conservative calculations and minimise the risk of perverse incentives, ERS is the entity responsible for performing these calculations, not the Developer. For details on how calculations impact units & issuance, please refer to ERS Programme.

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NORMATIVE REFERENCES

This document must be read in conjunction with:

- ERS Programme
- M001
- Reference Ecosystem Guidelines
- Zonation Guidelines
- Standard Setting and Methodology Development Procedure

TEMPLATES

This document is linked with the following templates:

- Leakage Mitigation Template
- Additionality Sheet

READING NOTES

- To simplify readability, the Quantification Methodology will assume one Restoration Site and one Reference Site per Project, even though multiple sites may exist.
- Colour code:
  - Every element underlined in gold refers to an ERS template, guidelines or supporting document.
  - Every element *underlined in black italic* refers to another section of the Standard.
  - Every element underlined in green refers to a weblink.
- Definitions can be found in Terminology & References.
- Reading indications:

💡 These sections offer complementary insights into the Methodology, offering more in-depth information on future improvements or details on specific topics to facilitate comprehension.

📌 These sections provide examples to illustrate technical requirements of the Methodology.

Boundaries

PROJECT BOUNDARIES

The Project boundaries relevant to this methodology are the Restoration Site, the Reference Site, and the Leakage Belt. The physical boundaries delimit all the carbon pools, emission sinks, and emission sources considered in the Quantification Methodology.

EMISSION SINKS & SOURCES

1. List of Relevant GHG Sinks

Relevant carbon pools included as emission sinks in the Quantification Methodology are listed below. Carbon pools are considered emission sinks if the Project absorbs GHG emissions from the atmosphere.

Carbon Pool	Type	Inclusion	Justification
Woody biomass	Aboveground	Yes	Significant carbon pool
	Belowground	Yes	Significant carbon pool
Non-woody biomass	Aboveground	Yes	Significant carbon pool
	Belowground	Yes	Significant carbon pool
Soil organic carbon (SOC)		No	Measurement uncertainties, conservative to exclude

Soil inorganic carbon (SIC)	No	Measurement uncertainties, conservative to exclude
Dead wood	No	Conservative to exclude
Litter	No	Conservative to exclude
Harvested wood products	No	Out of scope for this methodology

2. List of Relevant GHG Sources

Relevant carbon pools included as emission sources in the Quantification Methodology are listed below. Carbon pools are considered emission sources in the event of reversals or leakage.

Carbon Pools	Type	Leakage	Reversal	Justification
Woody biomass	Aboveground	Yes	Yes	Significant carbon pool
	Belowground	Yes	Yes	Significant carbon pool
Non-woody biomass	Aboveground	Yes	Yes	Significant carbon pool
	Belowground	Yes	Yes	Significant carbon pool
Soil organic carbon (SOC)		No	No	Measurement uncertainties & not relevant to M001 (soil inversion >25 cm not allowed)

Soil inorganic carbon (SIC)	No	No	Measurement uncertainties
Dead wood	No	N/A	Measurement uncertainties
Litter	No	N/A	Measurement uncertainties
Harvested Wood Products	No	N/A	Not relevant to M001 (commercial harvesting not allowed)

Listed below are other emission sources that have been excluded from the Quantification Methodology and the rationale for their exclusion.

Emission sources	Justification
Burning of biomass	Out of scope for this methodology (not allowed)
Emissions from nitrogen fertilisers	Out of scope for this methodology (not allowed)
Burning of fossil fuels	*De minimis*

💡 Note that the only GHG covered in the scope of this methodology is carbon dioxide.

Carbon Stock *Quantification*

INITIAL CARBON STOCK

This step is used to estimate the initial baseline of the Restoration Site.

1. Land Cover Assessment

A land cover assessment is performed upon receipt of the Project shapefile. This assessment is performed to distinguish woody from non-woody areas within the Restoration Site.

💡 Remote sensing models quantifying AGB are solely trained on woody biomass and should not be used to estimate non-woody biomass. To assess carbon stocks accurately, ERS separates woody from non-woody areas and uses different datasets to estimate them.

1.1. **Woody/Non-woody mask.** The Project shapefile is transferred to an AGB Provider to obtain a woody/non-woody biomass mask, a raster format map that distinguishes the location and size of woody areas within the Restoration Site. Refer to *Appendix 1* for more details on the AGB provider.

1.2. **Non-woody areas classification.** An analysis is performed to distinguish the different primary classes of the remaining non-woody areas (water, shrubs, grasses, bare soil, crops and buildings). The latest version of the ten-metre ESA WorldCover model[1] is used to classify non-woody areas into specific land cover types (grasslands, shrublands, croplands, bare soils, built-up, and snow). This model

[1] At the time of publication, the 2021 v200 version. Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., et al. (2022). 'ESA WorldCover 10 m 2021 v200'. Available at: URL (Accessed 03/11/2023).

harnesses data from Sentinel-1 and Sentinel-2 satellites and employs machine-learning techniques to generate maps with a resolution of ten (10) metres.

2. Biomass Quantification of Woody and Non-Woody Areas

Separate approaches are then used to estimate AGB for woody and non-woody land cover classes.

2.1. Above Ground Biomass.

2.1.1. **Woody areas.** The AGB Provider generates a Woody AGB map that estimates the AGB at the pixel level in raster format for woody areas. This is referred to as $\mathbf{AGB}^{w}_{rest}$.

2.1.2. **Non-woody areas.** Various methods are employed to calculate non-woody AGB based on the information provided in the non-woody areas classification (1.2). Non-woody AGB is referred to as $\mathbf{AGB}^{n-w}_{rest}$.

- For shrublands, a default ratio of 0.1 is used to convert forest biomass to shrubland biomass according to the AR-TOOL14[2].
- For grasslands, a default value for each climate zone is selected, according to the IPCC, as demonstrated in *Appendix 2*.
- For bare soils and croplands, the AGB is estimated at 0.
- Non-forestable areas such as infrastructure and water bodies are excluded from the AGB quantification.

[2] UNFCCC. (2013). 'AR-TOOL14 A/R Methodological tool: Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities Version 04.1'. Available at: URL (Accessed 25/01/2023)

2.2. Below Ground Biomass.

2.2.1. **Woody areas.** The woody BGB is estimated to be a proportion of its AGB as dictated by the root-to-shoot ratio (RS). The relationship between BGB and AGB is represented by the equation (1):

$$\mathbf{BGB}^{w}_{rest} = \mathbf{AGB}^{w}_{rest} \times RS^{w} \quad (1)$$

Where:

- $\mathbf{BGB}^{w}_{rest}$ = Woody BGB at the Restoration Site; tDM.
- $\mathbf{AGB}^{w}_{rest}$ = Woody AGB at the Restoration Site; tDM.
- RS^{w} = Root-to-shoot ratio of woody biomass; dimensionless. The root-to-shoot ratios applied are based on the 2019 updated values from the IPCC, which provides root-to-shoot (RS) values for each ecological zone across continents (Asia, Africa, North and South America), distinguishing between above-ground biomass values less than and greater than 125 $tDM{\cdot}Ha^{-1}$. ERS uses values specific to natural origins[3]; dimensionless.

2.2.2. **Non-woody areas.** For non-woody terrains, the estimation of BGB follows the same equation as for woody areas, guided by the IPCC's root-to-shoot ratio (RS)[4], tailored to the specific climate zone. This approach ensures that the BGB estimation is reflective of the region's ecological and climatic characteristics.

[3] Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (2019). 'IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories'. Published: IPCC, Switzerland. Volume 4, Chapter 4, Table 4.4, p 4.18. Available at: URL (Accessed 27/05/2024)

[4] Eggleston, H S, Buendia, L, Miwa, K, Ngara, T, and Tanabe, K. (2006) 'IPCC Guidelines for National Greenhouse Gas Inventories. Japan.' Volume 4, Chapter 6, Table 6.4, p 6.27. Available at: URL (Accessed 03/11/2023).

Non-woody BGB is obtained using equation (2):

$$\mathbf{BGB}^{n-w}_{rest} = \mathbf{AGB}^{n-w}_{rest} \times RS^{n-w} \quad (2)$$

Where:

- $\mathbf{BGB}^{n-w}_{rest}$ = Non-woody BGB at the Restoration Site; tDM.
- $\mathbf{AGB}^{n-w}_{rest}$ = Non-woody AGB at the Restoration Site; tDM.
- RS^{n-w} = Root-to-shoot ratio of non-woody biomass. A default value is obtained from the IPCC for each climate zone; dimensionless.

2.2.3. For grasslands, the aggregated biomass (AGB and BGB) provided by the IPCC is used. Refer to *Appendix 2* for more details.

3. Total Biomass of the Restoration Site

The aggregated biomass comprises the above and below-ground biomass of the woody and non-woody components within the Restoration Site. The aggregated biomass is obtained using equations (3), (4) and (5):

$$\mathbf{B}^{w}_{rest} = \mathbf{AGB}^{w}_{rest} + \mathbf{BGB}^{w}_{rest} \quad (3)$$

Where:

- $\mathbf{B}^{w}_{rest}$ = Total woody biomass at the Restoration Site; tDM.
- $\mathbf{AGB}^{w}_{rest}$ = Woody AGB at the Restoration Site; tDM.
- $\mathbf{BGB}^{w}_{rest}$ = Woody BGB at the Restoration Site; tDM.

$$\mathbf{B}_{rest}^{n-w} = \mathbf{AGB}_{rest}^{n-w} + \mathbf{BGB}_{rest}^{n-w} \quad (4)$$

Where:

- $\mathbf{B}_{rest}^{n-w}$ = Total non-woody biomass at the Restoration Site; tDM.
- $\mathbf{AGB}_{rest}^{n-w}$ = Non-woody AGB at the Restoration Site; tDM.
- $\mathbf{BGB}_{rest}^{n-w}$ = Non-woody BGB at the Restoration Site; tDM.

$$\mathbf{B}_{rest} = \mathbf{B}_{rest}^{w} + \mathbf{B}_{rest}^{n-w} \quad (5)$$

Where:

- $\mathbf{B}_{rest}$ = Total biomass at the Restoration Site; tDM.
- $\mathbf{B}_{rest}^{w}$ = Total woody biomass at the Restoration Site; tDM.
- $\mathbf{B}_{rest}^{n-w}$ = Total non-woody biomass at the Restoration Site; tDM.

4. Biomass Conversion to CO2 Equivalents

Biomass in the Restoration Site is converted into CO2 equivalents (CO2e) to determine its total GHG removals.

The AR-TOOL14 A/R Methodological tool's equations[5] are used to translate biomass into carbon content and subsequently into CO2e. This ensures a consistent and standardised measurement aligned with global carbon reporting metrics.

[5] UNFCCC. (2013). 'AR-TOOL14 A/R Methodological tool: Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities Version 04.1'. Available at: URL (Accessed 25/01/2023)

The relation between carbon stock and tree biomass is obtained using equation (6).

$$\mathbf{C}_{rest} = \frac{44}{12} \times CF \times \mathbf{B}_{rest} \quad (6)$$

Where:

- $\mathbf{C}_{rest}$ = Carbon stock in the Restoration Site; tCO_2e.
- $\frac{44}{12}$ = Molecular weight ratio of CO2 to Carbon, which is $\frac{44}{12}$; dimensionless.
- CF = Carbon fraction of tree biomass; $tC \cdot tDM^{-1}$.
  A default value of 0.47 is adopted[6].
- $\mathbf{B}_{rest}$ = Total biomass at the Restoration Site; tDM.

The initial baseline is determined by the carbon stock ($\mathbf{C}_{rest}$) and is expressed in tonnes of CO2e.

FINAL CARBON STOCK

This step estimates the carbon stock of the Reference Site.

1. Selection of a Reference Site

1.1. ERS requests the selection and adoption of a Reference Ecosystem and geographical coordinates of a physical Reference Site.

1.2. The Project's Reference Ecosystem is used to inform the restoration objectives.

1.3. The Reference Site is used to quantify the GHG removal capacity of the Project.

[6] Eggleston, H S, Buendia, L, Miwa, K, Ngara, T, and Tanabe, K. (2006) 'IPCC Guidelines for National Greenhouse Gas Inventories. Japan.' Volume 4, Chapter 4 , Table 4.3, p 4.48. Available at: URL (Accessed 03/11/2023).

Refer to the Reference Ecosystem Guidelines for more information.

2. Carbon Stock at Reference Site

2.1. Upon submission of the Reference Site's shapefile, the AGB provider generates:

2.1.1. **A woody/non-woody biomass mask** in raster format, showing the distinction between woody and non-woody areas at the Reference Site.

2.1.2. **A woody AGB map** that estimates the AGB at the pixel level in raster format.

2.2. Woody BGB is obtained using AGB values from step 2.1.2, using equation (7):

$$\mathbf{BGB}^{w}_{ref} = \mathbf{AGB}^{w}_{ref} \times RS^{w} \qquad (7)$$

Where:

- $\mathbf{BGB}^{w}_{ref}$ = Woody BGB in the Reference site; tDM.
- $\mathbf{AGB}^{w}_{ref}$ = Woody AGB in the Reference site; tDM.
- RS^{w} = Root-to-shoot ratio,; dimensionless. The root-to-shoot ratios applied are based on the 2019 updated values from the IPCC, which provides root-to-shoot (RS) values for each ecological zone across continents (Asia, Africa, North and South America), distinguishing between above-ground biomass values less than and greater than 125 tDM/Ha. ERS uses values specific to natural origins[7].

[7] Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (2019). 'IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories'. Published: IPCC, Switzerland. Volume 4, Chapter 4, Table 4.4, p 4.18. Available at: URL (Accessed 27/05/2024)

2.3. The total biomass of the Reference Site is obtained using equation (8):

$$\mathbf{B}_{ref} = \mathbf{AGB}^{w}_{ref} + \mathbf{BGB}^{w}_{ref} \quad (8)$$

Where:

- $\mathbf{B}_{ref}$ = Total woody biomass at the Reference Site; tDM.
- $\mathbf{AGB}^{w}_{ref}$ = Woody AGB in the Reference Site; tDM.
- $\mathbf{BGB}^{w}_{ref}$ = Woody BGB in the Reference Site; tDM.

2.4. The conversion to CO2e is obtained using equation (9):

$$\mathbf{C}_{ref} = \frac{44}{12} \times CF \times \mathbf{B}_{ref} \quad (9)$$

Where:

- $\mathbf{C}_{ref}$ = Carbon stock on the Reference Site; tCO_2e.
- $\frac{44}{12}$ = Molecular weight ratio of CO2 to Carbon, which is $\frac{44}{12}$; dimensionless.
- CF = Carbon fraction of tree biomass; $tC \cdot tDM^{-1}$.
  A default value of 0.47 is used.
- $\mathbf{B}_{ref}$ = Total woody biomass at the Reference Site; tDM.

2.5. The average carbon stock in the Reference Site is calculated as an estimate of the carbon stock by size (in hectares). This process enables the utilisation of this data for further processing in the calculation of the Project's GHG removal capacity. The average carbon stock per hectare in the Reference Site is obtained using equation (10):

$$\overline{C}_{ref} = C_{ref}/A_{ref} \tag{10}$$

Where:

- $\overline{C}_{ref}$ = Mean carbon stock on the Reference Site, represents the mean CO2 sequestrated; $tCO_2e{\cdot}ha^{-1}$.
- C_{ref} = Carbon stock on the Reference Site; tCO_2e.
- A_{ref} = Area of the Reference Site; ha.

GHG REMOVAL CAPACITY

Using the initial and final carbon stocks, this step estimates the GHG removal capacity of the Restoration Site.

💡 In this methodology, ERS expects that the Restoration Site will reach carbon stock levels comparable to the Reference Site by the end of the crediting period.

1. GHG removal capacity of the Restoration Site

The GHG removal capacity of a terrestrial forest restoration Project is determined by calculating the difference between the carbon stock of the Reference Site and the current carbon stock of the Restoration Site. This is obtained using equation (11):

$$C_{potential} = (A_{project} \times \overline{C}_{ref}) - C_{rest} \tag{11}$$

Where:

- $\mathbf{C}_{potential}$ = Project's GHG removal capacity; tCO_2e.
- $\mathbf{A}_{project}$ = Size of the Restoration Site; ha.
- $\overline{\mathbf{C}_{ref}}$ = Mean carbon stock on the Reference Site; $tCO_2e \cdot ha^{-1}$.
- $\mathbf{C}_{rest}$ = Initial baseline of the Restoration Site; tCO_2e.

Adjustment Factors

EMISSIONS

1. Initial Leakage Quantification

This section describes how a Project's leakage is quantified at Certification.

1.1. For leakage quantification, ERS conservatively assumes that the carbon stock in Hosting Areas is reduced to 0.

1.2. If a Project undertook pre-submission activities that resulted in leakage, ERS will quantify carbon stock in the Hosting Areas and deduct it from the Project's net GHG removals.

1.2.1. Leakage resulting from Pre-submission activities is obtained for each Hosting Area using equation (12):

$$\mathbf{L}_i^{pa} = \mathbf{C}_{i,t} - \mathbf{C}_{i,t=0} \qquad (12)$$

Where:

- $\mathbf{L}_i^{pa}$ = Monitored leakage on the Hosting Area i; tCO_2e.
- $\mathbf{C}_{i,t}$ = Carbon stock in the Hosting Area where activity i is located at year t; tCO_2e.

1.3. At Certification, the Developer can declare potential leakage through the following methods:

1.3.1. If the Developer is able to provide the Hosting Area(s), ERS will estimate the potential impact represented by the leakage ($\mathbf{L}^{ha}$) using the same calculation process as for the Restoration Site, derived from equations (1), (2), (3), (4), (5) and (6).

1.3.2. If the Developer cannot provide the Hosting Area(s), they must identify Displaced Activity Areas and their estimated displacement percentage. To estimate the potential impact of the displacement(s), ERS will generate random sampling plots within the Leakage Belt and determine the average carbon stock of these sampling plots, following the same calculation process as for the Reference Site, derived from equations (7), (8), (9). The average carbon stock of the sampling plots in the Leakage Belt is obtained using equation (13):

$$\overline{\mathbf{C}_{s-plot}} = \mathbf{C}_{s-plot} / \mathbf{A}_{s-plot} \qquad (13)$$

Where:

- $\overline{\mathbf{C}_{s-plot}}$ = Mean carbon stock of the sampling plots in the Leakage Belt; $tCO_2e \cdot ha^{-1}$.
- $\mathbf{C}_{s-plot}$ = Carbon stock of the sampling plots in the Leakage Belt; tCO_2e.
- $\mathbf{A}_{s-plot}$ = Total Area of sampling plots; ha.

The estimated leakage is obtained using equation (14):

$$\mathbf{L}_i^p = \mathbf{A}_i \times \overline{\mathbf{C}_{s-plot}} \times \mathbf{P}_i \qquad (14)$$

Where:

- $\mathbf{L}_i^p$ = leakage estimated for a Displaced Activity Area i within the Project Area; tCO_2e.
- $\mathbf{A}_i$ = Land-surface of the Displaced Activity Area; ha.
- $\overline{\mathbf{C}_{s-plot}}$ = Mean carbon stock of the sampling plots in the Leakage Belt; $tCO_2e \cdot ha^{-1}$

- $\mathbf{P}_i$ = Declared % of displacement of the activity; dimensionless

1.4. Total leakage is obtained by aggregating leakage derived from the Hosting Area(s) (1.2.1) and equation (14), using equation (15):

$$\mathbf{L}^{d} = \sum_{i=1}^{n} \mathbf{L}_{i}^{ha} + \sum_{i=1}^{n} \mathbf{L}_{i}^{p} \tag{15}$$

Where:

- $\mathbf{L}^{d}$ = Total declared Leakage; tCO_2e.
- $\mathbf{L}_{i}^{ha}$ = Leakage of known Hosting Areas; tCO_2e.
- $\mathbf{L}_{i}^{p}$ = Leakage of Displaced Activity Areas; tCO_2e.

2. Leakage Correction

This section describes how initial leakage is corrected at year two (2) and/or year four (4) after Certification.

To quantify leakage, ERS compares the total carbon stock in the Hosting Areas before and after the activity displacements. The delta is deducted from the Project's total GHG removals.

$$\Delta\mathbf{L}_{t}^{c} = \sum_{i=1}^{n} (\mathbf{L}_{i,t}^{m} - \mathbf{L}_{i,t-1}^{m}),\ t \geq 1 \tag{16}$$

Where:

- $\Delta\mathbf{L}^{c}$ = Corrected Leakage; tCO_2e.

- $\mathbf{L}^{m}_{i,t}$ = Monitored GHG emissions from a Hosting Area i at Verification Cycle t; $\mathbf{L}^{m}_{i,t=0}$ = 0 tCO_2e.

3. Quantification of Loss Events

3.1. In case of a loss event, the GHG emissions of the Loss Area are quantified.

3.2. The carbon stock of the Loss Area is calculated before and after the loss event, following the *Initial Carbon Stock* calculation.

3.3. The carbon stock loss is obtained using equation (17):

$$\mathbf{C}_{loss-event} = \mathbf{C}_{post-event} - \mathbf{C}_{pre-event} \tag{17}$$

Where:

- $\mathbf{C}_{loss-event}$ = Impact of the loss event; tCO_2e.
- $\mathbf{C}_{post-event}$ = Carbon stock in the area after the loss event; tCO_2e
- $\mathbf{C}_{pre-event}$ = Carbon stock in the area before the loss event; tCO_2e

4. Loss Event Characterisation

4.1. Before Verification, ERS calculates the net GHG removals of the Verification Cycle, and categorises the loss event(s) of the period using equation (18):

$$\Delta\mathbf{C}_{t} = \mathbf{C}_{t} - \mathbf{C}_{t-1} \tag{18}$$

Where:

- $\Delta\mathbf{C}_t$ = Net GHG removals achieved during the Verification Cycle t; tCO_2e.
- $\mathbf{C}_t$ = GHG removals achieved at the end of the Verification Cycle t; tCO_2e.
- $\mathbf{C}_{t-1}$ = GHG removals achieved at the end of Verification Cycle $t-1$; tCO_2e.

4.2. If $\Delta\mathbf{C}_t < 0$, the loss event is considered as a reversal.

DYNAMIC BASELINE

1. Concept

1.1. A dynamic baseline evaluation consists of a periodic re-evaluation of the initial baseline scenario to adjust unit issuance.

1.2. The dynamic baseline process is performed before each Verification. This process will lead to the adjustment of unit issuance, if necessary, following procedures detailed in the *Units & Issuance* section of the ERS Programme.

1.3. To generate a dynamic baseline, ERS selects control plots located outside the Project Area and the Leakage Belt but with similar ecological and biophysical characteristics, including degradation levels. Shapefiles of these control plots will be disclosed in the Project Design Document and on the ERS Registry.

2. Project Clustering

2.1. **Concept**. Once the indicators are selected, the Restoration Site is stratified utilising the K-means clustering algorithm, a statistical technique that discerns natural patterns within the dataset and supports the identification of optimal clusters. Stratification involves the division of the Restoration Site into sub-zones based on the selected indicators listed in 2.2. Clusters refer to the grouping of naturally similar sub-zones, identified by the algorithm. For each sub-zone, median values for every indicator are calculated, minimising the impact of outliers and ensuring a robust analysis.

2.2. **Identification of Environmental Indicators.** Various environmental indicators covering ecological, climatic, and land use aspects are identified to determine sub-zones within the Restoration Site. Indicators include:

- Landcover[8]
- Elevation[9]
- Slope (Derived from Elevation)
- Forest Height[10]
- Soil Physical and Chemical Parameters (bulk density, coarse fragment, clay content, pH, SOC)[11]
- Biomes from IUCN classification
- Distance to Roads[12]

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[8] Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., et al. (2022). ESA WorldCover 10 m 2021 v200. Available at: URL. (Accessed 03/11/2023)

[9] Farr, T. G., et al. (2007). 'The Shuttle Radar Topography Mission'. Rev. Geophys., 45, RG2004. Available at: URL. (Accessed 03/11/2023)

[10] P. Potapov, X. Li, A. Hernandez-Serna, A. Tyukavina, M.C. Hansen, A. Kommareddy, A. Pickens, S. Turubanova, H. Tang, C.E. Silva, J. Armston, R. Dubayah, J. B. Blair, M. Hofton. (2020). 'Mapping and monitoring global forest canopy height through integration of GEDI and Landsat data'. Remote Sensing of Environment, 112165. Available at URL. (Accessed 03/11/2023)

[11] Poggio, L., de Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., and Rossiter, D.: SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty, SOIL, 7, 217–240, Available at: URL. (Accessed 03/11/2023)

[12] OpenStreetMap contributors. (2017). Available at: URL.

3. Selection of Control Plots

3.1. **Concept.** Areas or sub-zones that share similar characteristics to the clusters, located outside of the Restoration site and the Leakage Belt and referred to as control plots, are identified using the K-Nearest Neighbors (KNN) algorithm.

3.2. **Indicators.** The selection of control plots relies on the set of indicators selected in 2.2 and important political factors such as political physical boundaries. This ensures that the selected control plots are located in the same country and governed under the same jurisdiction as the Project Area.

💡 Land tenure and ownership are not included in this Methodology due to the lack of global and, in many cases, national land tenure registries that are available for public use.

3.3. **Exclusion of Inappropriate Areas**[13]. Regions within the study area unsuitable to be considered control plots are systematically excluded. These include:

- **Protected areas:** their conservation status does not ensure a real representation of a business-as-usual scenario.
- **Active carbon projects:** they do not ensure a real representation of a business-as-usual scenario, as both the Project and control plots are subject to the same treatment.
- **Commercial plantations:** these areas cannot act as control areas because a different treatment is applied. Commercial plantations differ significantly from restoration projects in

[13] IUCN and UNEP-WCMC (2022), The World Database on Protected Areas (WDPA) [On-line], Cambridge, UK: UNEP-WCMC. Available at: www.protectedplanet.net. Accessed through Global Forest Watch in (10/2023). www.globalforestwatch.org. Available at: URL.

incentive structures, in that there is typically a strong economic incentive for planting and harvesting the trees.

3.4. This approach guarantees that only genuinely comparable plots are considered for the Project, enhancing the precision of the selection process.

4. Dynamic Evaluation

Before each Verification, ERS performs a dynamic evaluation of the initial baseline.

4.1. **Refinement of Control Plots**. ERS verifies the relevance of control plots using the methodology detailed in the *Selection of Control Plots*. If it is found that the current control plots are no longer representative or applicable, the process involves regenerating new control plots.

4.2. **Assessment of Control Plots.** For each cluster, the average change in carbon stock across all control plots is obtained using equation (19).

$$\Delta \mathbf{B}_t^{c} = \sum_{i=1}^{n}\left[\left(\overline{\mathbf{C}_{t,i}^{cp}} - \overline{\mathbf{C}_{t-1,i}^{cp}} \right) \times A_i \right] \quad (19)$$

Where:

- $\Delta \mathbf{B}_t^{c}$ = Corrected Baseline at the Verification Cycle t; tCO_2e.
- $\mathbf{C}_{t-1,i}^{cp}$ = Mean carbon stock of the control plots that belong to the cluster i at Verification Cycle $t-1$; $tCO_2e \cdot ha^{-1}$.
- $\overline{\mathbf{C}_{t,i}^{cp}}$ = Mean carbon stock of the control plots that belong to the cluster i at Verification Cycle t; $tCO_2e \cdot ha^{-1}$.
- A_i = Project Area covered by cluster i; ha.

4.3. Following the assessment of control plots, two distinct scenarios can emerge:

4.3.1. If the mean carbon stock in control plots has shown an upward trend from Y0 to the present, indicating positive forest growth, the Project will adjust for this increase when calculating GHG removals and issuing units. In such a scenario, the Project cannot claim full credit for the GHG removals on its Restoration Site. A corrective mechanism is used to adjust the overestimated baseline. Refer to the *Units & Issuance* section of the ERS Programme for more details.

4.3.2. Conversely, if a decline in carbon stock is detected in the control plots, a corrective mechanism is applied to adjust the underestimated baseline. This mechanism involves adding GHG removals and their corresponding units to the Project. Refer to the *Units & Issuance* section of the ERS Programme for more details.

Carbon Stock *Accounting*

PRU ACCOUNTING

Total PRUs are obtained using the equation (20):

$$\mathbf{PRU} = \mathbf{C}_{\text{capacity}}^{\text{conservative}} - \mathbf{L}^{\text{conservative}} \tag{20}$$

Where:

- **PRU** = Projected Restoration Units; tCO_2e.
- $\mathbf{C}_{\text{capacity}}^{\text{conservative}}$ = Conservative Project's GHG removal capacity; tCO_2e.
- $\mathbf{L}^{\text{conservative}}$ = Total conservative declared Leakage at Project start; tCO_2e.

VRU ACCOUNTING

PRUs conversion into VRUs is performed every two (2) or four (4) years after Verification, and throughout the Project's crediting period. Before each Verification and to ensure the most accurate conversion of units, ERS measures carbon stock in the Restoration Site, factoring:

1. **Biomass evolution in the Restoration Site.** The carbon stock evolution at the Restoration Site is calculated by comparing the total biomass at Verification Cycle t, with the total biomass at Verification Cycle $t-1$. This evaluation includes any loss events that occurred on the Restoration Site during Verification Cycle t.

2. **Leakage correction.** The leakage evolution observed during the Verification Cycle t. Note that leakage is quantified and corrected accordingly only until year four.

3. **Baseline correction.** The carbon stock evolution monitored in the control plots during the Verification Cycle t.

Total VRUs for the Verification Cycle t are calculated following this given formula:

$$\mathbf{VRU}_t = \Delta\mathbf{C}_t^{\text{conservative}} - \Delta\mathbf{L}_t^{\text{c}} - \Delta\mathbf{B}_t^{\text{c}} \quad (21)$$

Where:

- $\mathbf{VRU}_t$ = Verified Restoration Unit for the Verification Cycle t; tCO_2e.
- $\Delta\mathbf{C}_t^{\text{conservative}}$ = Net conservative GHG removals achieved during the Verification Cycle t; tCO_2e.
- $\Delta\mathbf{L}_t^{\text{c}}$ = Corrected Leakage at the Verification Cycle t; if $t > 4$, $\Delta\mathbf{L}_t^{\text{c}} = 0$; tCO_2e.
- $\Delta\mathbf{B}_t^{\text{c}}$ = Corrected Baseline at the Verification Cycle t; tCO_2e.

Net conservative GHG removals estimation is determined by calculating the difference between the carbon state at the Verification Cycle t and the carbon state at the verification cycle $t-1$ minus their uncertainty, using the following formula:

$$\Delta\mathbf{C}_t^{\text{conservative}} = (\mathbf{C}_t - \mathbf{C}_{t-1}) - \sqrt{\Delta\mathbf{C}_t^{\ 2} + \Delta\mathbf{C}_{t-1}^{\ \ 2}} \quad (22)$$

Where:

- $\Delta\mathbf{C}_t^{conservative}$ = Net conservative GHG removals achieved during the Verification Cycle t; tCO_2e.
- $\mathbf{C}_t$ = Carbon stock state at the Verification Cycle t
- $\Delta\mathbf{C}_t$ = Uncertainty of the carbon stock state at the Verification Cycle t; tCO_2e.

Uncertainty & *Conservativeness*

This section describes how ERS accounts for uncertainty and the rules enforced to ensure conservative carbon estimations.

UNCERTAINTY

1. Woody AGB Estimation

To minimise and account for uncertainty related to AGB estimation, ERS implements best practices outlined in the Aboveground Woody Biomass Product Validation Good Practices Protocol[14]. This implies that:

1.1. AGB error estimation must be considered in the entire process, from field measurements to modelling errors, including those associated with allometric equations.

1.2. The propagation of uncertainty through these various stages must be effectively managed. ERS's AGB benchmark *(Appendix 1)* demonstrates different methods of AGB uncertainty propagation.

1.3. A 95% confidence interval for AGB values must be generated.

[14] Duncanson, L., Armston, J., Disney, M., Avitabile, V., Barbier, N., Calders, K., Carter, S., Chave, J., Herold, M., MacBean, N., McRoberts, R., Minor, D., Paul, K., Réjou-Méchain, M., Roxburgh, S., Williams, M., Albinet, C., Baker, T., Bartholomeus, H., Bastin, J.F., Coomes, D., Crowther, T., Davies, S., de Bruin, S., De Kauwe, M., Domke, G., Dubayah, R., Falkowski, M., Fatoyinbo, L., Goetz, S., Jantz, P., Jonckheere, I., Jucker, T., Kay, H., Kellner, J., Labriere, N., Lucas, R., Mitchard, E., Morsdorf, F., Naesset, E., Park, T., Phillips, O.L., Ploton, P., Puliti, S., Quegan, S., Saatchi, S., Schaaf, C., Schepaschenko, D., Scipal, K., Stovall, A., Thiel, C., Wulder, M.A., Camacho, F., Nickeson, J., Román, M., Margolis, H. (2021). Aboveground Woody Biomass Product Validation Good Practices Protocol. Version 1.0. In L. Duncanson, M. Disney, J. Armston, J. Nickeson, D. Minor, and F. Camacho (Eds.), Good Practices for Satellite Derived Land Product Validation, (p. 236): Land Product Validation Subgroup (WGCV/CEOS), Available at: URL.

2. Current AGB Model Uncertainty

Chloris' model used by ERS to obtain AGB Maps includes for every pixel an estimate of[15]:

2.1. The total change over the time series (i.e., gain or loss) calculated as the difference between the fitted values at the beginning and end points of the pixel-level trajectories;

2.2. The p-value (scaled 0-100) from a modified F-test associated with the pixel-level change estimate where p-values ≤ 5 represent a significant change (i.e., gain or loss) in Aboveground Biomass Density (AGBD) and values > 5 represent a non-significant change (i.e., no gain or loss/stable) in AGBD;

2.3. The standard error associated with the pixel-level change representing uncertainty in the change estimate at the 95% level. The uncertainty associated with the pixel-level estimates of AGBD change is obtained from the Map of Standard Error.

2.3.1. The standard error is estimated from an error propagation analysis carried out at the pixel level across all layers in the time series. The propagation of error, considering geolocation, allometric, and model-based errors, is initially used to estimate the standard error for the AGBD prediction at each point in the time series. This is most easily understood as the confidence interval (C.I.) for each pixel-level trajectory. This C.I. envelope is then used to calculate the standard error of the AGBD change. All AGBD change statistics reported are derived from sums of pixel values where the change (i.e., gain or loss) was determined to be significant (p-value ≤ 5).

2.3.2. The standard error at the pixel level is aggregated to the site level in a process that considers the spatial autocorrelation and is

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[15] Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D. and Houghton, R.A. (2017). 'Tropical forests are a net carbon source based on aboveground measurements of gain and loss'. Science, 358(6360), pp.230-234. Available at: URL (Accessed 3/11/2023)

used to compute the overall site-level uncertainty for the AGBD and change. The standard error at the pixel level (SE_{pixel}) is used to obtain the total standard error (SE_{total}) using equation (23):

$$SE_{total} = \sqrt{(1 - r)\sum\left(SE^2_{pixel}\right) + r\sum\left(SE_{pixel}\right)^2} \quad (23)$$

Where:

- SE_{total} = Total Standard Error; tDM.
- r = Correlation factor between the pixels. A default value of 0.01 is adopted.
- SE_{pixel} = Standard Error from the AGB provider for each pixel; tDM.

2.3.3. To obtain a conservative estimate of the AGB, the upper and lower 95% confidence limits will be calculated using the standard error. These limits are calculated by multiplying the total standard error (SE_{total}) by 1.96, which approximates the 97.5 percentile point of the normal distribution, as follows:

$$\Delta \mathbf{AGB}^{w,\, n-w} = 1.96 \times SE_{total} \quad (24)$$

Where:

- $\Delta \mathbf{AGB}^{w,\, n-w}$ = Woody or non-woody above-ground biomass uncertainty; tDM.
- SE_{total} = The total Standard Error; tDM.

3. Uncertainty propagation

ERS propagates uncertainties throughout the carbon quantification process by applying dedicated formulas for uncertainty propagation. This section outlines the specific formulas used.

3.1. **Below-Ground Biomass uncertainty.** To estimate belowground biomass (BGB), obtained from aboveground biomass (AGB) and the root-to-shoot ratio (RS), ERS accounts for the uncertainty in AGB while excluding the uncertainty in RS to prevent the double-counting of uncertainties. By subtracting the uncertainty from the AGB before calculating BGB, ERS achieves a conservative estimate, effectively managing measurement variabilities. This method ensures realistic and reliable BGB estimates, even at the minimum plausible AGB values, and prevents artificial inflation of total uncertainty. This implies:

$$\Delta \mathbf{BGB}^{\text{w, n–w}}_{\text{rest, ref}} = 0 \qquad (25)$$

Where:

- $\Delta \mathbf{BGB}^{\text{w, n–w}}_{\text{rest, ref}}$ = Woody or non-woody below-ground biomass uncertainty for the Restoration Site or the Reference Site; tDM.

3.2. Biomass uncertainty. The general biomass uncertainty, derived from equations (3) and (4) for the Restoration Site and equation (8) for the Reference Site, applicable to both woody and non-woody areas, is obtained using equation (26):

$$\Delta \mathbf{B}^{\text{w, n–w}}_{\text{rest, ref}} = \sqrt{\left(\Delta \mathbf{AGB}^{\text{w, n–w}}_{\text{rest, ref}}\right)^2 + \left(\Delta \mathbf{BGB}^{\text{w, n–w}}_{\text{rest, ref}}\right)^2} \qquad (26)$$

Where:

- $\Delta\mathbf{B}^{w,\,n-w}_{rest,\,ref}$ = Woody or non-woody biomass uncertainty, for Restoration Site or Reference Site; tDM.
- $\Delta\mathbf{AGB}^{w,\,n-w}_{rest,\,ref}$ = Woody or non-woody above-ground biomass uncertainty, for Restoration Site or Reference Site; tDM.
- $\Delta\mathbf{BGB}^{w,\,n-w}_{rest,\,ref}$ = Woody or non-woody below-ground biomass uncertainty, for Restoration Site or Reference Site; tDM. Here, this value is considered to be equal to zero (as explained in section 3.1).

3.3. Total biomass uncertainty. The total biomass uncertainty, derived from equation (5), is obtained using equation (27):

$$\Delta\mathbf{B} = \sqrt{\left(\Delta\mathbf{B}^{w}\right)^{2} + \left(\Delta\mathbf{B}^{n-w}\right)^{2}} \tag{27}$$

Where:

- $\Delta\mathbf{B}$ = Total biomass uncertainty; tDM.
- $\Delta\mathbf{B}^{w}$ = Total woody biomass uncertainty; tDM.
- $\Delta\mathbf{B}^{n-w}$ = Total non-woody biomass uncertainty; tDM.

3.4. Biomass Conversion to CO2 Equivalents uncertainty. The carbon stock uncertainty formula, derived from equation (6) for the Restoration Site and (9) for the Reference Site, is obtained by:

$$\Delta\mathbf{C}_{rest,\,ref} = \frac{44}{12} \times CF \times \Delta\mathbf{B}_{rest,\,ref} \tag{28}$$

Where:

- $\Delta\mathbf{C}_{rest,\,ref}$ = Carbon stock uncertainty for the Restoration Site or the Reference Site; tCO_2e.
- $\frac{44}{12}$ = Molecular weight ratio of CO2 to Carbon, which is $\frac{44}{12}$;

dimensionless.

- CF = Carbon fraction of tree biomass; $tC \cdot tDM^{-1}$. A default value of 0.47 is adopted.
- $\Delta \mathbf{B}_{rest,\, ref}$ = Total biomass uncertainty, for Restoration Site or Reference Site; tDM.

3.5. **Average carbon stock uncertainty.** The average carbon stock per hectare uncertainty, derived from equation (10) for the Reference Site and (13) for the sampling plots, is obtained using equation (29):

$$\Delta\overline{\mathbf{C}_{ref,s-plot}} = \Delta \mathbf{C}_{ref,s-plot} / \mathbf{A}_{ref,s-plot} \qquad (29)$$

Where:

- $\Delta\overline{\mathbf{C}_{ref,s-plot}}$ = Mean carbon stock uncertainty, for Reference Site or sampling plots; $tCO2e \cdot ha^{-1}$
- $\Delta \mathbf{C}_{ref,s-plot}$ = Total carbon stock uncertainty for Reference Site or sampling plots; tCO_2e.
- $\mathbf{A}_{ref,s-plot}$ = Size of the Reference Site or sampling plots; ha.

3.6. **Leakage uncertainty.** Uncertainty related to leakage of Displaced Activity Areas, derived from equation (14), is obtained using equation (30):

$$\Delta \mathbf{L}_i^{p} = \mathbf{A}_i \times \Delta\overline{\mathbf{C}_{s-plot}} \times \mathbf{P}_i \qquad (30)$$

Where:

- $\Delta \mathbf{L}_i^{p}$ = Leakage uncertainty computed for each Displaced Activity Areas i; tCO_2e.
- $\mathbf{A}_i$ = Land-surface of the activity i within the Project Area; ha.

- $\Delta \overline{\mathbf{C}_{s-plot}}$ = Mean carbon stock uncertainty of the sampling plots in the Leakage Belt; $tCO_2e \cdot ha^{-1}$
- $\mathbf{P}_i$ = Declared % of displacement of the activity i; dimensionless.

3.7. **Total leakage on the project uncertainty.** The uncertainty of the total leakage declared is obtained using equation (31):

$$\Delta \mathbf{L}^{d} = \sqrt{\left(\Delta \mathbf{L}^{ad}\right)^2 + \left(\Delta \mathbf{L}^{p}\right)^2} \quad (31)$$

Where:

- $\Delta \mathbf{L}^{d}$ = Total leakage uncertainty; tCO_2e.
- $\Delta \mathbf{L}^{ad}$ = Leakage area uncertainty for Hosting Areas; tCO_2e.
- $\Delta \mathbf{L}^{p}$ = Leakage area uncertainty for Displaced Activities Areas; tCO_2e.

CONSERVATIVENESS

The conservative approach applied by ERS consistently and systematically selects the uncertainty boundary that leans towards the safe side. This prevents any potential overestimation of GHG removals. In addition, uncertainty parameters calculated in the *Uncertainty* section are factored in.

The following section provides details about the conservative approach taken at each step.

1. **GHG Removal Capacity**

1.1. **Initial Carbon Stock**. When quantifying carbon stock of the initial baseline, the upper band of the 95% confidence interval is selected for Woody AGB values.

1.2. **Final Carbon Stock.** When quantifying carbon stock of the Reference Site, the lower band of the 95% confidence interval is chosen.

1.3. **GHG Removal Capacity.** Having applied a conservative approach in quantifying the initial baseline scenario at the Restoration Site and the Reference Site, the GHG Removal Capacity resulting from the difference between the two is implicitly conservative.

Additionally, ERS increases the baseline value of the Restoration Site by incorporating its associated uncertainty, which is derived from equation (26). Concurrently, ERS decreases the baseline value of the Reference Site by subtracting its associated uncertainty, which is derived from equation (27). This is expressed as:

$$\mathbf{C}_{capacity}^{conservative} = \left[\mathbf{A}_{project} \times \left(\overline{\mathbf{C}_{ref}} - \Delta\overline{\mathbf{C}_{ref}}\right)\right] - \left(\mathbf{C}_{rest} + \Delta\mathbf{C}_{rest}\right) \tag{32}$$

Where:

- $\mathbf{C}_{capacity}^{conservative}$ = Project's GHG removal capacity with a conservative approach; tCO_2e.
- $\mathbf{A}_{project}$ = Size of the Restoration Site; ha.
- $\overline{\mathbf{C}_{ref}}$ = Mean carbon stock on the Reference Site, represents the mean CO2 sequestrated; $tCO_2e{\cdot}ha^{-1}$.
- $\Delta\overline{\mathbf{C}_{ref}}$ =Mean carbon stock uncertainty on the Reference Site; $tCO_2e{\cdot}ha^{-1}$.
- $\mathbf{C}_{rest}$ = Initial carbon stock of the Restoration Site; tCO_2e.
- $\Delta\mathbf{C}_{rest}$ = Initial carbon stock uncertainty of the Restoration Site; tCO_2e.

2. **Leakage.** To ensure a conservative approach, ERS adds the leakage uncertainty, which is derived from equation (29), to the leakage value. The conservative estimate of leakage is obtained using equation (33):

$$\mathbf{L}^{conservative}_{potential} = \mathbf{L}^{d} + \Delta\mathbf{L}^{d} \tag{33}$$

Where:

- $\mathbf{L}^{conservative}_{potential}$ = Project's declared leakage with a conservative approach; tCO_2e.
- $\mathbf{L}^{d}$ = Total declared Leakage; tCO_2e
- $\Delta\mathbf{L}^{d}$ = Total leakage uncertainty; tCO_2e.

3. **Biennial Quantification.** The same conservative approach is applied to measure the carbon stock of the Restoration Site before every Verification.

   3.1. The lower band of the 95% confidence interval is selected for Woody AGB values.

   3.2. The woody or non-woody biomass uncertainty, derived from equation (26), is retrieved from the biomass stock.

4. **Loss Events.** An inherent challenge in assessing the impacts of loss events is determining the BGB loss through satellite imagery. ERS conservatively considers a complete loss of BGB and consequently deducts both AGB and BGB from the carbon stock quantification.

Appendix 1 - *AGB Provider*

BENCHMARK PROCESS

The selection of an accurate AGB provider is crucial in ensuring precise carbon estimation. A benchmarking approach was employed to identify the most suitable AGB provider for ERS. The process overview is described below, for more detailed information refer to the AGB Benchmark.

1. Initial Provider Contact

Multiple AGB providers were approached to participate in the benchmarking process. Each received a shapefile document with geographic information of a forested area, to apply their AGB models and determine their values.

2. Model Output Comparison

ERS employs the AGB model outputs from each provider to gather essential statistical information. This information is compared among the various providers. Furthermore, a detailed comparison is conducted in certain sub-areas of the model against a designated reference model.

3. Selection Criteria

3.1. **Precision.** The accuracy of the AGB model in predicting biomass values.

3.2. **Uncertainty Analysis.** The methodology for calculating uncertainty and how it is propagated from field measurements all the way to the final AGB model.

3.3. **Coverage.** The extent of the area the model could cover and its flexibility in application.

3.4. **Integration Feasibility.** The ease and efficiency of integrating the model into the ERS certification process.

4. Conclusion

Based on the criteria, the most appropriate AGB provider was selected to ensure rigorous, conservative and accurate data is integrated in this Quantification Methodology. For this version of the Methodology, Chloris Geospatial has been selected as the AGB provider.

In instances where Chloris Geospatial is unable to supply timely AGB maps for required areas, ERS has appointed Kanop as an alternative AGB provider to ensure continuous data availability.

5. Iteration

The benchmark process can be repeated at any time, and at least every two (2) years, following Standard Setting and Methodology Development Procedure. ERS seeks to use data providers that apply the principles and rigour described in this Methodology, as such, an updated benchmark process allows ERS to ensure the proper selection of its AGB provider.

Undertaking a repeated benchmark process in the future can result in changing the AGB provider. Should ERS make this decision, it will be openly communicated in its methodology documents.

Appendix 2 - *IPCC Data Grassland*

ERS selects IPCC[16] default values by climate zone for above and below-ground biomass in grasslands, as described in the table 6.4. and shown below:

TABLE 6.4
DEFAULT BIOMASS STOCKS PRESENT ON GRASSLAND , AFTER CONVERSION FROM OTHER LAND USE

IPCC climate zone	Peak above-ground biomass[1] (tonnes d.m. ha^{-1})	Total (above-ground and below-ground) non-woody biomass[2] (tonnes d.m. ha^{-1})	Error [3]
Boreal – Dry & Wet[4]	1.7	8.5	± 75%
Cold Temperate – Dry	1.7	6.5	± 75%
Cold Temperate –Wet	2.4	12	± 75%
Warm Temperate – Dry	1.6	6.1	± 75%
Warm Temperate –Wet	2.7	13.5	± 75%
Tropical – Dry	2.3	8.7	± 75%
Tropical - Moist & Wet	6.2	16.1	± 75%

[1] Data for standing biomass are compiled from multi-year averages reported at grassland sites registered in the ORNL DAAC NPP database [http://www.daacsti.ornl.gov/NPP/].

[2] Total above-ground and below-ground biomass values are based on the peak above-ground biomass values, and the below-ground biomass to aboveground biomass ratios (Table 6.1).

[3] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

[4] Due to limited data, dry and moist zones for the boreal temperature regime and moist and wet zones for the tropical temperature regime were combined.

[16] Eggleston, H S, Buendia, L, Miwa, K, Ngara, T, and Tanabe, K. (2006) 'IPCC Guidelines for National Greenhouse Gas Inventories. Japan.' Volume 4, Chapter 6, Table 6.4, p 6.27. Available at: URL (Accessed 03/11/2023).

Appendix 3 - *Carbon Parameters*

Data/Parameter	**AGB^w**
Data unit	tDM/ha
Description	Above ground biomass density
Equations	(1), (3), (7), (8)
Source of the data	AGB provider (Chloris)
Measurement methods and procedures	Aboveground woody biomass is measured using satellite imagery
Monitoring frequency	Annually
QA/QC procedures	**Quality Assurance** - The selection of an accurate AGB provider is crucial in ensuring precise carbon estimation. A benchmarking approach using independent reference data computed using a different approach than the one used by the remote sensing model (TLS + UAV-LS) was employed to identify the most suitable AGB provider for ERS. The process overview is described below, for more detailed information refer to the Benchmark Process. - The AGB model has to be trained on independent data distributed into multiple regions and biomes. - In order to generate robust, annual biomass change estimates, seasonal effects should be minimised using preprocessing techniques. - The validation of the model needs to be performed on independent higher-quality data spread across different regions and biomes collected using different kinds of approaches like ALS or field plots. **Quality Control** Two different site-level quality procedures are triggered - A series of automated tests within the pipeline that detect things such as anomalies e.g. impossible values. The system

	also produces quality statistics. - A GIS analyst performs a second QA/QC. Tests include: visual review on possible artefacts such as climatic or BRDF effects and, if required verifying data and changes with high resolution imagery.
Purpose of data	Estimate the carbon sequestration state of a given area

Data/Parameter	RS^{w}
Data unit	dimensionless
Description	The root-to-shoot ratios applied are based on the 2019 updated values from the IPCC, which provides root-to-shoot (RS) values for each ecological zone across continents (Asia, Africa, North and South America), distinguishing between above-ground biomass values less than and greater than 125 tDM·Ha-1. ERS uses values specific to natural origins.
Equations	(1), (7)
Source of the data	IPCC
Values applies	Region-specific
Purpose of data	Estimate the woody BGB based on the AGB value on woody area

Data/Parameter	RS^{n-w}
Data unit	dimensionless
Description	Root-to-shoot ratio of non-woody biomass. A default value is obtained from the IPCC for each climate zone; dimensionless.
Equations	(2)
Source of the data	IPCC
Values applies	Region-specific

Purpose of data	Estimate the non-woody BGB based on the AGB value on non- woody area

Data/Parameter	CF
Data unit	tC/tDM
Description	Carbon fraction of dry biomass
Equations	(6), (9), (28)
Source of the data	IPCC 2006 Guidelines for National Greenhouse Gas Inventories
Value applied	0.47
Purpose of data	Convert the dry matter to carbon

Data/Parameter	BDR
Data unit	Dimensionless
Description	Ratio of shrub biomass per hectare
Source of the data	UNFCCC. (2013). 'AR-TOOL14 A/R Methodological tool: Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities Version 04.1'. Available at: URL
Value applied	0.10
Purpose of data	Estimating the AGB of shrublands

Data/Parameter	A_{ref}
Data unit	ha
Description	Reference site area
Equations	(10), (32)

Source of the data	Calculated from GIS data
Value applied	Project-specific
Measurement methods and procedures	Calculated from GIS data
QA/QC procedures	The Reference site area is validated visually using GIS tools and satellite data

Data/Parameter	Land cover
Data unit	ha
Description	Land cover of the project area
Source of the data	The latest available state of the art land cover model (eg. ESA, ESRI, World Cover,...)
Value applied	Project-specific
QA/QC procedures	**Quality Assurance** The land-cover model is selected using available papers, such as Global 10 m Land Use Land Cover Datasets: A Comparison of Dynamic World, World Cover and Esri Land Cover **Quality Control** A visual review is performed to compare the land cover with high-resolution imagery.

Data/Parameter	SE_{pixel}
Data unit	tDM
Description	Standard Error from the AGB provider for each pixel
Equations	(23)
Source of the data	AGB provider (Chloris)
Value applied	Project-specific

Monitoring frequency	Annually
Purpose of data	Estimate the uncertainty of a given AGB value

Data/Parameter	r
Data unit	Dimensionless
Description	Correlation factor between the pixels.
Equations	(23)
Source of the data	AGB provider (Chloris)
Value applied	0.01
Purpose of data	Capturing the spatial autocorrelation

Data/Parameter	Forest cover
Data unit	ha
Description	Forest cover loss map of the project area
Source of the data	The latest available state of the art forest cover loss model (eg. Global forest watch, LUCA,...)
Measurement methods and procedures	Forest cover loss is estimated by the forest cover loss model using satellite imagery.
Monitoring frequency	Monthly
QA/QC procedures	**Quality Assurance** The forest cover loss model used during the certification is selected according to the latest available scientific literature. The model is then accessed automatically via an API and computed to generate alerts and/or detailed reports. This ensures data is current, accurate, and consistent across all evaluations. **Quality Control** A visual review is performed by Certification Agents to compare the forest cover loss with high-resolution imagery.
Purpose of data	Estimate the forest cover loss to alter on loss events and

	leakage.

Data/Parameter	Control plots
Description	Controls plots used for the dynamic baseline
Equations	(19)
Source of the data	ERS models
Measurement methods and procedures	The control plots are defined using an automated process as described in the *Dynamic baseline* section
Monitoring frequency	Each verification cycle
QA/QC procedures	**Quality Assurance** The selection of control plots is performed using various environmental indicators that cover ecological, climatic, and land-use aspects and following the state of the art approach. **Quality Control** A visual review is randomly performed to control the quality of the selected control plot.
Purpose of data	The control plots are used for a periodic re-evaluation of the initial baseline scenario to adjust unit issuances.

Data/Parameter	Hosting area
Description	Declared hosting area of a given leakage activity
Equations	(14)
Source of the data	Developer
Measurement methods and procedures	Once Developers identify where leakage activities are displaced, they must create shapefiles on the ERS App to accurately determine the location and extent of these activities.
Monitoring frequency	Hosting areas are informed at Year 2 and Year 4 of Project

	implementation.
QA/QC procedures	**Quality Assurance** Developers must consult local stakeholders to get a precise understanding of the leakage activities and the needs to displace them. They must provide details about the activity's displacement in the Leakage Mitigation Template and on the ERS App. **Quality Control** The Certification Agents must verify data entries to identify and correct any discrepancies. A satellite imagery review is performed to control the surface of the selected hosting area. The inputs are securely stored to prevent unauthorised access, tampering, or loss. A log is maintained to record errors and corrective actions taken.
Purpose of data	

Data/Parameter	$\mathbf{P}_i$
Data unit	Dimensionless
Description	Declared % of displacement of the activity
Equations	(14)
Source of the data	Developer
Measurement methods and procedures	If Developers don't know where leakage activities are displaced, they must determine what surface of leakage activities will be displaced based on the Displaced Activity Area.
Monitoring frequency	Declared % of displacement of the activity are monitored at Year 2 of Project implementation.
QA/QC procedures	**Quality Assurance** Developers must consult local stakeholders to get a precise understanding of the leakage activities and the needs to displace them. They must provide details about the activity's displacement in the Leakage Mitigation Template and on the ERS App.

	Quality Control The Certification Agents must cross-check data with the Livelihoods interventions to verify that the leakage mitigation plan corresponds to the percentage informed. The inputs are securely stored to prevent unauthorised access, tampering, or loss. A log is maintained to record errors and corrective actions taken.
Purpose of data	Estimate the percentage of the displaced activity area

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