PLAN VIVO

PV Climate Tool

PT#SOC

Estimation of Change in Soil Organic Carbon

Version 1.0

21 October 2025

Developed by:

TerraCarbon www.terracarbon.com, The Landscapes and Livelihoods Group (TLLG) www.landscapesandlivelihoods.com, and Natural State www.naturalstate.org

Contributors: Laura Castañeda Gomez (laura.cgomez@terracarbon.com), Jaclyn Kachelmeyer, Nicholas Berry, Jenny Langan-Farmer

Approved by:

Enter details of the Methodology Approval Panel (MAP) members that approved the tool.

PLAN VIVO

Contents

1 Summary

The tool is applied within the PV Climate Agriculture and Forestry Carbon Benefit Assessment Methodology (**PM001**). It provides procedures for estimating changes in soil organic carbon (SOC) stocks in PV Climate project areas under baseline and project scenarios. Procedures include using in-situ measurements, process-based models validated with in-situ measurements, and the use of conservative default values to determine values for the following parameters that are used to estimate baseline and project removals in SOC following **PU001**:

$\Delta C_{SOC\_BSL,t}$ Change in carbon stock in soil organic carbon under the baseline scenario within the project area in year t (t CO_2e)

$C_{SOC_{BSL,t2,i}}$ Average carbon stock in soil organic carbon in the control plots for baseline scenario stratum *i* in year *t2* (t CO_2e/ha; either measured or modelled with model predictions validated by measurements)

$C_{SOC_{BSL,t1,i}}$ Average carbon stock in soil organic carbon in the control plots for baseline scenario stratum *i* in year *t1* (t CO_2e/ha; either measured or modelled with model predictions validated by measurements)

$\Delta C_{SOC\_PROJ,t}$ Change in carbon stock in soil organic carbon under the project scenario within the project area in year t (t CO_2e)

The tool is applicable globally to project areas in cropland, grassland, shrubland, savanna, woodland, and forestland; and project interventions that increase the carbon stored in soils.

Compliance with the relevant Methodology Requirements is summarised in Appendix 1.

2 Sources

This tool applies the following PV Climate Methodology elements:

- **PT003** Guidance for the Use of Models Validated with Measurements in PV Climate Projects V1.0
- **PU001** Estimation of Baseline and Project GHG Removals by Carbon Pools in Plan Vivo Projects, V1.2
- **PU005** Estimation of Uncertainty of Carbon Benefit Estimates in Plan Vivo projects V1.1

3 Definitions

The tool follows all definitions in the latest versions of the PV Climate Glossary and **PM001**, and the following definitions:

Model initialization = The foundational process of setting the initial parameters, states, or weights of a computer model, simulation, or machine learning algorithm before it begins training or executing a simulation

Shrubland = Areas dominated by woody or herbaceous shrubs typically less than 2–5 meters tall.

Savanna = A mixed woodland-grassland system where trees are widely spaced enough that the canopy does not close, typically maintaining 10% to 40% tree cover over a continuous grass layer.

Woodland = A more densely treed area than a savanna but more open than a forest, generally characterized by 40% to 60% (or more in some systems) tree cover where the canopy is still somewhat open, allowing sunlight to reach a grass or shrub understory.

4 Applicability Conditions

The tool is applicable globally to project areas and project interventions that meet the following conditions:

a) Land cover in the project area is either cropland, grassland, shrubland, savanna, woodland, or forestland in both the baseline and project scenarios. Project interventions that involve a change between two types of land cover, for example shrubland to woodland, are also allowed.

b) The project intervention results in an increase in SOC stocks.

The tool is not applicable under the following conditions:

c) Project areas on wetlands, peatlands, or waterlogged soils

d) Project areas that experience natural disturbance (e.g., flooding or landslides) with a frequency that makes their occurrence within the project period likely.

5 Procedures

Change in soil organic carbon stocks in project areas or control plots can be estimated with the following approaches:

i) In-situ measurements (see Section 5.1)

ii) Process-based modelling (see Section 5.2)

iii) Applying conservative estimates of SOC accumulation (see Section 5.3)

Details of the procedures for each of these approaches are described below.

5.1 In-situ Measurements

The in-situ measurement approach requires collecting physical soil samples in the project area or control plots at the project start (t_0) and over time to determine the change in SOC stocks in the baseline scenario (for control plots, if using dynamic baseline procedures) and/or project scenario, to estimate actual C removals with SOC accumulation.

Where direct measurements are collected for both baseline control sites and project scenarios, the sampling, laboratory, and calculation procedures described in Sections 5.1.1, 5.1.2 and 5.1.3 must be the same.

5.1.1 Sampling Procedures

When physically sampling for SOC, projects must implement a representative, unbiased sampling design that ensures enough statistical power to detect changes in SOC stocks, which can be slow to accrue, on expected verification timeframes. Project sampling design and sample analysis must adhere to the requirements below.

5.1.1.1 Sampling Design

Since SOC has high spatial variability, projects should implement a spatially stratified, random sampling design to quantify SOC stocks in the project area at t_0 and over time during the project crediting period. Stratified random sampling requires the project area to be delineated and then subdivided into relatively homogenous units, i.e., strata. Strata must be defined based on factors likely to influence SOC stocks and stock change, such as soil classification or texture, topography, climate, and historical land use and vegetation. If using dynamic baseline procedures, the baseline scenario strata defined following **PU001** must be used. The relevance of the selected environmental variables to the SOC pool must be demonstrated, for example with reference to peer-reviewed literature sources. Where project proponents have access to historical data or reconnaissance sampling, stratification can also be achieved based on prior information on SOC stocks to ensure known variability and patterns are captured in stratification.

Sample points are then allocated randomly within strata. If the dynamic baseline approach is used, control areas are matched to the defined project area strata based on the criteria detailed in **PU001**, Annex 3.

Stratified random sampling could be further integrated into other sampling designs, such as staged (i.e., multistaged, hierarchical, nested, or similar sampling designs). Where SOC stocks and expected stock change in the project area is known or demonstrated to be relatively homogenous, grid sampling may also be suitable.

For monitoring events, projects may use one of two approaches to collect in-situ samples:

1. **Independent sampling:** a new set of sample points is generated for each sampling event. Strata may change over time[1].
2. **Pairwise sampling:** the same sample points are revisited over time. Strata must remain fixed over time.

Resources for developing an appropriate sampling design include Aynekulu et al. (2011)[2], FAO (2019; 2020)[3,4], and de Gruijter et al. (2016)[5].

The project should determine and report the following components of the sampling design, following the guidance below:

1. Description of the statistical approach underpinning the sampling design (e.g., stratified random sampling).
2. Map, KML, and description of strata present in the project area, including the factors considered in stratification.

[1] This approach may require higher sampling intensity and represent a challenge for a dynamic baseline approach as the control sites defined at the start of the project may not fall within newly defined strata in the project area, if they were to change in monitoring events.

[2] Aynekulu, E., Vagen, T-G., Shephard, K., Winowiecki, L. 2011. A protocol for modeling, measurement and monitoring soil carbon stocks in agricultural landscapes. Version 1.1. World Agroforestry Centre, Nairobi. https://www.cifor-icraf.org/publications/downloads/Publications/PDFS/TM11192.pdf

[3] FAO. 2019. Measuring and modelling soil carbon stocks and stock changes in livestock production systems: Guidelines for assessment (Version 1). Livestock Environmental Assessment and Performance (LEAP) Partnership. Rome, FAO. 170 pp. Licence: CC BY-NC-SA 3.0 IGO. https://openknowledge.fao.org/server/api/core/bitstreams/3573cc7c-f8b0-42cc-bead-ea56c502647e/content

[4] FAO. 2020. A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes – GSOC-MRV Protocol. Rome. https://doi.org/10.4060/cb0509en

[5] Gruijter, J. J. de, A. B. McBratney, B. Minasny, I. Wheeler, B. P. Malone, y U. Stockmann. «Farm-Scale Soil Carbon Auditing». Geoderma 265 (2016): 120-30. https://doi.org/10.1016/j.geoderma.2015.11.010.

3. The statistical approach used to determine sampling locations and the number of samples in each stratum.
4. Field protocols, including the use of composite samples and collection of ancillary data, such as grazing intensity, vegetation types, and disturbance history at sample points.
5. Laboratory protocols.
6. QA/QC procedures for field measurements and lab analyses.

5.1.1.2 Sampling Intensity

Projects should conduct a power analysis to determine the minimum number of samples needed per stratum to detect the expected change in SOC stocks between monitoring events. Preliminary data regarding the distribution of the mean initial SOC stocks and expected SOC stock change between monitoring events in the project area are required to carry out a power analysis. Data can be sourced from reconnaissance sampling, digital soil maps, national soil inventories or similar, and/or peer-reviewed literature. Appropriate statistical procedures for a power analysis are provided by standard software, or a statistical calculator can be used (Faul et al. 2007)[6].

While there is not a required minimum number of samples, sampling should adequately represent the project area. Projects should allocate the number of sample points per stratum based on the stratum's relative size and/or expected variance in SOC stock change, where larger strata and/or strata with high spatial heterogeneity are allocated a higher number of sample points (e.g., Neyman allocation).

FAO (2019) provides guidance on conducting a power analysis to determine the sample size needed to detect a minimum change in SOC stocks with statistical confidence. The goal is to ensure that the smallest detectable change given a sample size of n exceeds the expected change in SOC stocks, accounting for variability. A modified version of the FAO (2019) equation is provided below:

$$MDD \geq \frac{S}{\sqrt{n}} \times (t_\alpha + t_\beta)$$

Equation 1

[6] Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007 May;39(2):175-91. doi: 10.3758/bf03193146. PMID: 17695343.

$$n \geq \left(\frac{S \times (t_\alpha + t_\beta)}{MDD}\right)^2$$

Equation 2

Where:

MDD Minimum detectable difference in SOC stocks between t_0 and t_x (tCO_2e)

S Standard deviation of the SOC stock change between t_0 and t_x (tCO_2e)

n Number of samples

t_α Two-sided critical value of the t-distribution at a given significance level (α) frequently taken as 0.05 (5%)

t_β One-sided quartile of the t-distribution corresponding to a probability of type II error β (e.g., 90%)

5.1.1.3 Field Procedures

Soil sampling may change depending on the selected approach used to report SOC stocks. Two options are valid: the fixed depth approach (FD) or the equivalent soil mass (ESM) approach. In the FD approach, soil samples are collected on predefined depth intervals (e.g. 0-30 cm, 30-60cm), that remain consistent for the baseline and monitoring sampling campaigns. SOC stocks are then calculated within these fixed depth intervals, regardless of changes in soil bulk density over time. The ESM approach on the other hand, accounts for changes in bulk density derived from project activities. Instead of sampling to a defined depth, the goal is to sample to a fixed mass of soil per unit area, which may require sampling at different depth intervals at baseline and monitoring events, to capture and report SOC stocks from the same soil mass across time.

The selection of the approach will impact the calculation method of the SOC stocks and its accuracy and careful consideration should be taken when selecting one approach over the other. The ESM approach is now preferred for SOC stock calculation and reporting of changes over time as it has higher accuracy, precision and comparability. Nevertheless, the FD approach may be acceptable if the project proponent can demonstrate that the project activity has not significantly impacted bulk density measurements over time. The only valid demonstration of no changes in bulk density for monitoring events are direct measurements done for either all sampling points or a smaller subsample of sampling points.

For either approach, field soil sampling has different considerations for the baseline and monitoring events. For the baseline, a minimum recommended sampling depth is 30 cm either collected as depth intervals (e.g. 0-10 cm, 10-20 cm and 20-30 cm) or as a single soil core (0-30cm). For the monitoring events, two options may be implemented, depending on how confident the project is that BD has not significantly changed since the baseline sampling event:

Option 1: Evidence-based fixed depth approach (higher risk)

If there is robust prior evidence (e.g. results from a pre-monitoring bulk density check in representative project plots or from long-term experimental data using the same land management practices) that the project activities do not significantly alter bulk density, then a fixed depth sampling approach (e.g., 0–30 cm) may be used at the monitoring events without introducing bias in SOC stock comparisons. In this case, SOC stocks can be reported over the same 0–30 cm depth used at baseline. However, it remains mandatory to measure bulk density during the monitoring event to validate that bulk density has indeed remained stable across the project area. The risk with this approach is that if monitoring bulk density results contradict the prior evidence, and no samples were collected beyond 30 cm, it will not be possible to apply the Equivalent Soil Mass (ESM) method post-hoc. This would prevent accurate correction for BD changes and may invalidate temporal SOC stock comparisons.

Option 2: ESM-ready approach (recommended)

To ensure flexibility and avoid risk, it is strongly recommended to collect soil samples beyond 30 cm, typically by adding a depth interval from 30- 50 cm. Both depth interval samples (0-30 and 30-50 cm) should be taken to the laboratory and kept as separate samples. Initially, only the 0-30 cm samples should be processed for SOC and bulk density. Once the bulk density results from the 0-30 cm depth interval are known, assess whether it has significantly changed relative to the bulk density in the baseline. If bulk density has not changed, the 30-50 cm samples can be discarded or archived and SOC and bulk density reported over 0-30 cm (fixed depth). If bulk density has significantly changed, then the 30-50 cm samples should be processed for both SOC and bulk density to enable the ESM-based SOC stock calculation.

The diameter of the tool used to extract the sample and the sampling depths should be recorded for bulk density calculation.

Field procedures should employ the following best practices:

- Samples are collected during the same season over time, avoiding recent tillage and/or organic amendment applications.

- All organic material (manure, crop residues, roots, etc) must be cleared from the soil surface prior to sample.
- The intended and actual sample point GPS locations are recorded.
- Field edges are avoided to minimize edge effects.
- Areas that are not under project interventions are not sampled and are excluded from the project area.

Projects can collect samples for SOC content and bulk density in a number of ways:

1. SOC content and bulk density are measured from the same sample for every sample collected.
2. SOC content and bulk density are measured from the same sample, but only a portion of all samples are analysed for bulk density.
3. SOC content and bulk density are measured from separate but nearby samples at all sample points (e.g., separate points within 5 m of each other; e.g., bulk density is collected at the centre of a sample plot, from which a composite sample for SOC content is also collected).
4. SOC content and bulk density are measured from separate sample points, with fewer bulk density samples collected overall.

Bulk density typically shows less spatial variation horizontally than SOC content. Thus, projects may collect fewer bulk density samples overall to balance practical constraints with spatial representation. This approach assumes spatial uniformity of bulk density, which may not hold true across landscapes with significant topographic variation (e.g., upper slope vs lower slope positions) or areas with different management practices and soil types. At minimum, separate bulk density samples should be collected to represent each strata, landscape position, or management zone.

Organic Carbon Content Samples

Projects should use either a soil corer or auger to collect samples for SOC content. Other tools (e.g., shovels) are not permitted due to their imprecision. Projects may collect samples for organic carbon content analysis at either individual points (e.g., a single core) or from small plots in which subsamples within a plot are combined and homogenized into a single composite sample. When samples are composited, the compositing procedure must be clearly reported. It is critical that samples are not combined across different depths. Compositing must only occur between samples from the same depth increment (e.g., 0-30, 0–20, 20-40 cm).

Bulk Density Samples

Different approaches can be used to collect soil samples for bulk density estimation (e.g., core method, clod, excavation sampling, volume infill method, and gamma radiation). Bulk density methods must follow established standards and best practices, such as ISO 11272:2017 "Soil quality - Determination of dry bulk density."[7]

Bulk density using the core method is recommended but may not be suitable for all soils (e.g., very stony soils). Sampling probes/cores should remain consistent throughout a project since probe/core diameter can affect bulk density measurements (Sharma et al., 2019)[8]. When driving in a core, care should be taken to avoid compaction. A notable sign of compaction is when the soil level begins to drop in relation to the marker on the coring tube or when resistance occurs.

In addition, soil augers can also be used in collecting bulk density samples, provided QA/QC procedures are used to ensure the depth, diameter, and volume of the sampling hole is known. When a Dutch auger is used, it is recommended that a sampling plate is placed on the soil surface to collect to ensure all the soil is collected (see LDSF Field Manual)[9]. However, Dutch augers are not recommended for bulk density sample collection but instead, used only for the ESM approach as they disturb the soil structure and do not extract a core of known volume, required for bulk density calculation.

5.1.2 Laboratory Procedures

Soil samples should be and transported to the laboratory in a cooler and analysed as soon as possible after collection. Prior to analysis, samples should be stored in a cold room or fridge (but not frozen) to minimize microbial activity leading to CO2 respiration and reduction of SOC stocks. Where both bulk density and soil organic carbon content will be analysed from the same sample, the bulk density analysis must be performed first.

5.1.2.1 Sample Preparation: Weighing, Drying, and Sieving

[7] https://www.iso.org/standard/68255.html

[8] Sharma, Sumit, Tracy Wilson, Tyson Ochsner, y Jason G. Warren. «Sampling Probes Affect Bulk Density and Soil Organic Carbon Measurements». Agricultural & Environmental Letters 5, n.o 1 (2020): e20005. https://doi.org/10.1002/ael2.20005.

[9] Vågen, T.-G., & Winowiecki, L. A. (2023). The Land Degradation Surveillance Framework (LDSF): Field manual for land and soil health assessments [PDF]. Center for International Forestry Research & World Agroforestry (CIFOR-ICRAF). https://www.cifor-icraf.org/publications/pdf/flyer/LDSF-Field-Manual.pdf

Soil samples need to be weighed at field-moisture and after dried, and before and after sieving with a 2 mm sieve. This information is used to calculate the gravimetric water content and the weight of coarse fragments. Total soil mass is corrected with the gravimetric water content, whereas the sample volume is corrected with the weight of the coarse fragments. These procedures should be done separately per depth interval collected and carried as follows:

1. Weight the field-moist soil sample and record the weight
2. Spread the sample in a heat-resistant tray and dry in an over (105°C) until constant weight (ensuring all water has evaporated)
3. Weight the dried soil sample and record the weight
4. Calculate the gravimetric water content (GWC):

$$GWC = \frac{(wet\ mass - dry\ mass)}{dry\ mass}$$

Equation 3

Where:

GWC Gravimetric Water Content (percent)

$wet\ mass$ Mass of the soil sample collected prior to oven drying (g) or field-moist soil sample

$dry\ mass$ Mass of the soil sample collected after oven drying (g)

Note: The GWC can be determined on a soil subsample instead of the whole sample. For this, 10-20 g of field-moist soil sample is weighed, dried and re-weighed after dried (steps 1-3) to calculate GWC (step 4).

5. Sieve the dried soil sample through a 2 mm sieve, where coarse fragments (gravel, stones, rocks, or other particles > 2 mm) will be removed and only the mineral soil sample will pass through the sieve. The coarse fragments left in the sieve have to be weighed and their weight recorded to calculate the corrected sample volume. If any plant material (e.g. roots, fine roots) pass through the sieve, they must be removed by hand from the sample.

5.1.2.2 Correction of Total Soil Mass and Sample Volume

Total soil mass is corrected with the gravimetric water content, whereas the sample volume is corrected with the weight of the coarse fragments measured in the procedures above (see Section 5.1.2.1).

6. The corrected soil mass of the sample, accounting for the gravimetric water content, equates to the dry weight of the total sample if the entire sample mass was oven dried. If a subsample was taken to determine GWC, then the following equation is applied to determine the corrected dry mass of the entire sample:

$$Dry\ mass_{corr} = mass_{air-dired} - (mass_{air-dried} \times GWC)$$

Equation 4

Where:

$Dry\ mass_{corr}$	Dry mass of the full soil sample, corrected for moisture content (g)
$mass_{air-dired}$	Mass of the full sample after drying (g)
GWC	Gravimetric Water Content (percent; see Equation 3)

7. To correct the sample volume to account for the space occupied by coarse fragments, calculate first the sample volume. Sample volume is determined based on the diameter (D) of the auger sampler used and the length of the depth increment for a given sample.

$$Sample\ volume_{uncorr} = \pi\left(\frac{D}{2}\right)^2 \times length$$

Equation 5

Where:

$Sample\ volume_{uncorr}$	Volume of the sample collected, uncorrected for coarse fragments (cm3)
π	pi, roughly equivalent to 3.142 (unitless)
D	Diameter of the sample tool, e.g., core or auger (cm)
$length$	Length of the sample depth increment (cm)

8. Finally, correct the calculated sample volume with the coarse fragments weight using the following formula, in which the bulk density of coarse fragments is assumed to be 2.4 g/cm^3.

$$Sample\ volume_{corr} = Sample\ volume_{uncorr} - \left(\frac{mass_{coarse\ frags}}{2.4}\right)$$

Equation 6

Where:

$Sample\ volume_{corr}$ Volume of the sample collected corrected for coarse fragments (cm³)

$Sample\ volume_{uncorr}$ Volume of the sample collected, uncorrected for coarse fragments (cm3; see Equation 5)

$mass_{coarse\ frags}$ Mass of coarse fragments >2 mm collected after sieving (g)

2.4 Standard density of coarse fragments (g/cm³)

5.1.2.3 Bulk Density Determination

Bulk density is calculated using the corrected calculated values of the soil mass (accounting for its gravimetric water content; see Equation 3) and the sample volume (accounting for the mass of the coarse fragments; see Equation 6).

Corrected bulk density is then calculated as:

$$BD_{corr} = \frac{Dry\ mass_{corr}}{Sample\ volume_{corr}}$$

Equation 7

Where:

BD_{corr} Bulk density of the soil sample, corrected for soil moisture content and the volume of coarse fragments (g cm³)

$Dry\ mass_{corr}$ Dry mass of the full soil sample, corrected for moisture content (g; see Equation 4)

$Sample\ volume_{corr}$ Volume of the sample collected corrected for coarse fragments (cm³; see Equation 6)

5.1.2.4 Soil Organic Carbon Concentration Analysis

Soil organic carbon should be measured using either dry combustion or ex situ spectroscopy in the laboratory. Walkley Black (wet) oxidation and loss on ignition (LOI) are not recommended but are permissible where other methods are not feasible. Emergent in-situ spectroscopy methods are also allowed with proper calibration with the dry combustion as the reference analytical approach.

- **Determination of SOC via dry combustion**: Dried soil samples are finely ground (<250 µm) with mortar and pestle or a grinding mill. Where the soil has high inorganic carbon concentration (e.g., soils with pH > 7.0), carbonates should be removed using acid pre-treatment. Certified standards, blanks, and duplicates must be included to ensure quality control and the reliability of SOC measurements.

- **Determination of SOC via spectroscopy:** Near-infrared (700-2500 nm) and mid-infrared (2500-25,000 nm) spectroscopy are alternatives to predict SOC. Best practice for SOC via spectroscopy have been established, such as *Supplement to the Soil 2021 Methodology Determination*[10].
  - The same spectrometer should be used during the lifetime of the project.
  - Soil samples for vis-NIR are crushed to pass a ≤2mm sieve, while mid-IR samples must pass a ≤0.5 mm mesh sieve or finer. Samples should be prepared following the same approach at t_0 and subsequent project sampling, as well as in the baseline scenario if direct measurement is also applied.
  - Model calibration and validation: The spectroscopy model used to predict SOC content must be validated using the tool **PT003** *Guidance for the Use of Models Validated with Measurements in PV Climate Projects*.
  - The calibration model and spectrum library used to create spectroscopy-based SOC prediction algorithms should be recorded. It is recommended that project-specific calibration datasets are used (i.e., the model is trained on a portion of samples collected within or near the project area that have been measured for SOC content using dry combustion).
  - The calibration model must include datasets that capture local soil types, carbon levels, and environmental variables in the project area. A model may perform well against calibration or independent validation datasets, but if the spectral library does not match the target region's characteristics, the results may be misleading. This can impair SOC monitoring over time, compromising project goals.
  - The gravimetric SOC concentrations in the training set must be associated with their respective spectra to generate the spectroscopic model.
  - The reference background spectrum must represent 100% reflection across the spectral range, with no more than 5% noise.

[10] DCCEEW 2024, Supplement to the Carbon Credits (Carbon Farming Initiative – Estimation of Soil Organic Carbon Sequestration using Measurement and Models) Methodology Determination 2021, Department of Climate Change, Energy, the Environment and Water, Canberra, October. CC BY 4.0.

- **Soil Organic Matter (SOM) Analysis**: When dry combustion methods are unavailable, the Walkley-Black method can serve as an alternative approach to estimate SOC. It determines oxidizable organic carbon. The Walkley-Black method must be performed in accordance with the Soil Organic Carbon Walkley-Black Method Titration and Colorimetric Method guidelines (FAO, 2019). Projects are encouraged to identify and use modified Walkley-Black analyses that are locally relevant to enhance accuracy and suitability to regional soil conditions. The conversion factor for estimating SOC from SOM varies depending on soil type, climatic conditions, and other regional factors. Therefore, proponents should review literature specific to the region to determine the appropriate factor, citing the source of the selected factor in the analysis. In the absence of region-specific data, the commonly used default factor of 0.58 may be applied. However, this default value must be explicitly stated, along with clear documentation of any assumptions or limitations associated with applying a universal factor. Where the colorimetric method is used, the conversion factor of 1.3 must be used (FAO, 2019).
- **In-situ Spectroscopy Methods**: Handheld spectrometry devices (e.g. portable mid-IR or NIR sensors) are allowed provided the same device or device model is used consistently throughout the project lifetime, and the project proponent provides proof of proper calibration and validation against a reference analytical method (dry combustion) using project-specific or locally representative samples.
    - The spectral model used must be documented, including details on the calibration dataset, model performance (e.g., R^2, RMSE), and any stratification or sub-setting approaches applied. The model must be evaluated for representativeness of the local soil types, carbon ranges, and environmental conditions.
    - Model uncertainty estimates, raw spectra, and geolocation of all sampling readings must be retained for auditability. The same sample preparation protocol (e.g., drying and sieving) should be applied consistently over time (baseline and monitoring events), and supported by peer-reviewed or standardized protocols (e.g., ICRAF or Rossel et al., 2016).
    - Instrument background spectrum quality and signal noise must be monitored regularly to ensure the reliability of field measurements.
    - In general, the use of these devices should follow the same principles as laboratory-based SOC determination via spectroscopy, including rigorous

calibration, standardized sample handling, and traceable data management. Instrument background spectrum quality and signal noise must be monitored regularly to ensure the reliability of field measurements.

5.1.3 Sample Point Calculation Procedures

SOC stocks are calculated using the results of the corrected BD (Equation 7) and the soil organic carbon concentration obtained from the laboratory (Section 5.1.2.4) and calculated separately for each depth interval defined by the project. The selected approach must be used for the entire project crediting period. Where the baseline scenario is directly measured or modelled, the same calculation approach must be applied in both the project and baseline scenarios. SOC stock calculations are different, depending on the approach used, either the Equivalent Soil Mass or fixed depth.

Fixed-depth approach

SOC stocks for the fixed-depth approach are calculated for the 0-30 cm depth sampled (and for each depth interval e.g. 0-10, 10-20 and 20-30 cm if applicable) in the baseline and concurrent monitoring events if BD is demonstrably unchanged. SOC stocks are calculated as:

$$SOC_{i,p,d} = OC_{i,p,d} \times BD_{corr,i,p,d} \times length_{i,p,d} \times 0.1 \times \frac{44}{12}$$

Equation 8

Where:

$SOC_{i,\mathrm{p,d}}$ Soil organic carbon stock in stratum *i* at sample point *p* within sample depth layer *d* (tCO_2e/ha)

$OC_{i,p,d}$ Soil organic carbon content in stratum *i* at sample point *p* within sample depth layer *d* (g/kg)

$BD_{corr,i,p,d}$ Corrected bulk density in stratum *i* at sample point *p* within sample depth layer *d* (g/cm^3; see Equation 7)

$length_{i,p,d}$ Length of sample depth increment d for sample point *p* in stratum *i* (cm)

0.1 Conversion to tonnes (unitless)

$\frac{44}{12}$ Molar mass of CO_2 used to convert to tCO_2e (unitless)

If several depth intervals were sampled at the baseline (e.g. 0-10 cm, 10-20 cm and 20-30 cm) SOC stocks (t CO_2eq/ha) should be added up to report the total 0-30 cm core SOC stocks.

Equivalent soil mass (ESM) approach

For the ESM approach, the projects should calculate the soil mass collected at the baseline sampling campaign taking into account the corrected BD and its depth (min 30 cm):

$$Reference\ soil\ mass_{i,p,d} = BD_{corr,i,p,d} \times length_{i,p,d} \times 0.1$$

Equation 9

Where:

$Reference\ soil\ mass_{i,p,d}$ Soil mass in stratum *i* at sample point *p* within sample depth layer *d* (t/ha)

$BD_{corr,i,p,d}$ Corrected bulk density in stratum *i* at sample point *p* within sample depth layer *d* (g/cm^3; see Equation 7)

$length_{i,p,d}$ Length of sample depth increment d for sample point *p* in stratum *i* (cm)

0.1 Conversion to tonnes (unitless)

If several depth intervals were sampled at the baseline (e.g. 0-10 cm, 10-20 cm and 20-30 cm) soil mass (t/ha) should be added across depth intervals to report the total 0-30 cm core soil mass. This soil mass is the reference mass that needs to be collected in future monitoring events. For pairwise sampling, the same soil mass needs to be reached per sampling point, whereas for independent sampling, the reference soil mass is the average soil mass within a strata.

Different methods can be used for SOC calculations when using the ESM approach. The interpolation method is recommended. Projects can follow the procedures outlined by McBratney and Minasny (2010)[11], Wendt and Hauser (2013)[12], von Haden et al. (2020)[13], or Ferchaud et al. (2023)[14] but should calculate ESM on a mineral soil mass basis. The spreadsheet provided by Wendt and Hauser (2013), modified to use mineral mass, or the R script provided by von Haden et al. (2020) may be used for calculations.

5.1.4 Calculation of SOC Stock at a Project Level

5.1.4.1 Average SOC in Control Areas

When soil samples are used to estimate SOC stocks in control areas, average SOC in each baseline scenario stratum at a point in time is calculated with Equation 10.

$$C_{SOC_{BSL,t,i}} = \frac{\sum_{p=1}^{n} SOC_{i,p,d}}{n}$$

Equation 10

Where:

$C_{SOC_{BSL,t,i}}$ Average carbon stock in soil organic carbon in the control plots for baseline scenario stratum *i* in year *t* (t CO_2e/ha)

$SOC_{i,p,d}$ Soil organic carbon stock in stratum *i* at sample point *p* within sample depth layer *d* (tCO_2e/ha; see Section 5.1.3)

n Number of sample points

5.1.4.2 Calculation of Change in SOC Stocks in Project Areas

When soil samples are used to estimate change in SOC stocks in the project areas, change in carbon stock is calculated with Equation 11 and Equation 12.

[11] McBratney, Alex B., and Budiman Minasny. "Comment on "Determining soil carbon stock changes: Simple bulk density corrections fail"[Agric. Ecosyst. Environ. 134 (2009) 251–256]." Agric Ecosyst Environ 136.12 (2010): 185-6.

[12] Wendt, J. W.; Hauser, S. An Equivalent Soil Mass Procedure for Monitoring Soil Organic Carbon in Multiple Soil Layers. European Journal of Soil Science 2013, 64 (1), 58–65. https://doi.org/10.1111/ejss.12002.

[13] Haden, A. C.; Yang, W. H.; DeLucia, E. H. Soils' Dirty Little Secret: Depth-based Comparisons Can Be Inadequate for Quantifying Changes in Soil Organic Carbon and Other Mineral Soil Properties. Glob Change Biol 2020, 26 (7), 3759–3770. https://doi.org/10.1111/gcb.15124.

[14] Ferchaud, F., Chlebowski, F., & Mary, B. (2023). SimpleESM: R script to calculate soil organic carbon and nitrogen stocks at Equivalent Soil Mass (Doctoral dissertation, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement (INRAE)).

$$\Delta C_{SOC\_PROJ,t} = \frac{C_{SOC_{PROJ,t2,i}} - C_{SOC_{PROJ,t1,i}}}{T}$$

Equation 11

Where:

$\Delta C_{SOC\_PROJ,t}$ Change in carbon stock in soil organic carbon under the project scenario within the project area in year *t* (t CO_2e)

$C_{SOC_{PROJ,t2,i}}$ Carbon stock in soil organic carbon in the project area in year *t2* (t CO_2e; see Equation 12)

$C_{SOC_{PROJ,t2,i}}$ Carbon stock in soil organic carbon in the project area in year *t1* (t CO_2e; see Equation 12)

T Time between *t1* and *t2* (years)

$$C_{SOC_{PROJ,t,i}} = \sum_{i=1}^{x} \frac{\sum_{p=1}^{n} SOC_{i,p,d}}{n} \times A_i$$

Equation 12

Where:

$C_{SOC_{PROJ,t,i}}$ Carbon stock in soil organic carbon in the project area in year *t* (t CO_2e)

$SOC_{i,p,d}$ Soil organic carbon stock in stratum *i* at sample point *p* within sample depth layer *d* (tCO_2e/ha; see Section 5.1.3)

n Number of sample points

A_i Extent of project area in stratum *i* (ha)

x Number of strata

5.2 Process-based Modelling

Projects can use a process-based model to simulate SOC stock changes in the project area under the baseline and project scenario, for the expected and actual SOC stock change.

5.2.1 Modelling Baseline Removals in SOC

In this approach, soil samples are collected only at t_0 to initialise the model. Since the dynamic baseline approach is not applicable for process-based modelling, subsequent sampling in the baseline scenario is not possible as SOC stock changes after t_0 could only be measured in the project area and thus would be representative of the project scenario. Projects applying a process-based model to represent the baseline scenario must follow the procedures below:

- The process-based model must be calibrated and validated following the procedures **PT003**.
- The model must be run for sample points within the project area, selected through a representative sampling design.
- Baseline model simulations at selected sample points must be initialised using soil samples taken from +/- 5 years of the start of the project intervention.
- Baseline model simulations at selected sample points must use input parameter data collected according to the requirements and guidelines below.
- For estimating expected changes in SOC model simulations should use expected weather conditions, ideally using predicted climate under modelled climate change scenarios for the relevant time frame. If such datasets are not available, average historical weather over a recent time frame can be used.
- For estimating actual carbon benefits achieved baseline model simulations must be run ex-post, using ex-post weather data representative of the sample point.

5.2.1.1 Sample Point Selection

Model simulations must be initialized using direct measurements of SOC stocks at t_0. Projects must follow the sampling design guidance and requirements in Section 5.1.1.1 to select the sample points within the project area at which model simulations representing the baseline scenario will be run at project start (t_0) and for the duration of the crediting period. Since the baseline scenario cannot be remeasured in the project area through time, sample points (and thus calibration points) for the baseline scenario are fixed at the locations where t_0 samples are collected. This means that for the process-based modelling approach, pairwise sampling is the only appropriate sampling approach method over time. Where models are used in the baseline scenario and to estimate actual project removals, the baseline and project scenario should have the same sampling design and sample points at t_0 using the same t_0 stocks in both scenarios.

5.2.1.2 Model Initialization With t_0 Soil Samples

SOC models must be initialized using direct in-situ measurements of SOC stocks at sample points taken within five years of the start of the project intervention. Model initialization or "spin-up" procedures are at the discretion of the project but must be reported. Where modelling is also employed to estimate actual project removals, the same modelling initialization procedures and parameter sets must be implemented as those used to initialize and run baseline simulations for the same sampling point.

Remeasurement of in-situ SOC stocks and re-initialization or re-calibration of the model is not required over time in the baseline scenario since baseline SOC stocks cannot be remeasured after t_0.

5.2.1.3 Model Input Parameters – Data Sources

Projects must collect the necessary input data to run model simulations for a given sample point. Required input data will depend on the model selected and may include management activities that are expected to occur under the baseline scenario (as determined following Section 6 in **PM001**), biophysical parameters, and ex-post precipitation and temperature conditions. Management data should be collected from one or a combination of the following sources, where available:

- Records and/or attestation from the project participants;
- Remote sensing variables, where remote sensing can be demonstrated as suited to the detection of specific practices or parameters (e.g., tillage or cropping activities);
- Surveys or focus group discussions of the project participants; and/or
- Regional averages or common-practice, as determined by peer-reviewed literature, government surveys/census, or similar third party data for the country or subnational jurisdiction in which the project is located.

Biophysical parameters may be determined through direct measurement, remote sensing data, digital soil maps, nearby weather stations, synthetic weather stations (e.g., PRISM), or similar, as suited to the specific input parameters.

5.2.1.4 Model Simulations and Baseline Stock Change Estimation

Modelled SOC stocks in the baseline scenario are determined at each sample point in year t and then aggregated to the stratum and project level following the equations below.

SOC stocks in year t of the verification period are modelled for each sample point using the relevant input variables collected ex-post based on actual management and weather.

$$C_{SOC\_BSL,h,n,t} = f_{SOC}(InptA_{h,n,t}, InptB_{h,n,t}, \ldots)$$

Equation 13

Where:

$C_{SOC\_BSL,h,n,t}$ Estimated soil organic carbon stocks in the baseline scenario for stratum h at sample point n in year t of the verification period (tCO_2e/ha)

f_{SOC} Model simulation in the baseline scenario for stratum h at sample point n in year t of the verification period

$InptA_{BE,i,t}$ Value for input variable A for stratum h at sample point n in year t of the verification period

$InptB_{BE,i,t}$ Value for input variable B for stratum h at sample point n in year t of the verification period

The areal mean SOC stock in year t of the verification period for stratum h in the baseline scenario is calculated as:

$$\underline{C_{SOC\_BSL,h,t}} = \frac{1}{N}\sum_{n=1}^{N} C_{SOC\_BSL,h,n,t}$$

Equation 14

Where:

$\underline{C_{SOC\_BSL,h,t}}$ Areal mean SOC stocks in the baseline scenario in stratum h in year t of the verification period (tCO_2e/ha)

$C_{SOC\_BSL,h,n,t}$ Estimated soil organic carbon stocks in the baseline scenario for stratum h at sample point n in year t of the verification period (tCO_2e/ha; see Equation 13)

N Number of sample points in stratum h

Total SOC stocks across all project areas in year t of the verification period are calculated as the sum of stocks in each stratum:

$$C_{SOC\_BSL,t} = \sum_{i=1}^{H} \underline{C_{SOC\_BSL,h,t}} \times A_i$$

Equation 15

Where:

$C_{SOC\_BSL,t}$ SOC stocks in the baseline scenario in year t of the verification period (tCO_2e)

$\underline{C_{SOC\_BSL,h,t}}$ Areal mean SOC stocks in the baseline scenario in stratum h in year t of the verification period (tCO_2e/ha; see Equation 14)

A_i Area of stratum i (ha)

H Number of strata in the project

Change in SOC stocks in the baseline scenario is calculated as:

$$\Delta C_{SOC\_BSL,t} = \frac{C_{SOC\_BSL,t2} - C_{SOC\_BSL,t1}}{T}$$

Equation 16

Where:

$\Delta C_{SOC\_BSL,t}$ Change in carbon stock in soil organic carbon under the baseline scenario within the project area in year t (t CO_2e)

$C_{SOC\_BSL,t2}$ SOC stocks in the baseline scenario in year *t2* of the verification period (tCO_2e; see Equation 15)

$C_{SOC\_BSL,t1}$ SOC stocks in the baseline scenario in year *t1* of the verification period (tCO_2e; see Equation 15)

T Time between *t1* and *t2* (years)

5.2.2 Modelling Expected Project Removals in SOC

Process-based modelling of SOC stock change expected in the project scenario follows the procedures for modelling baseline removals in SOC in Section 5.2.1, with the following modifications:

- Simulations are run based on expected management activities in the project scenario.
- All parameters with the subscript *SOC_BSL* representing SOC stocks and stock changes in the baseline scenario should be replaced with the subscript *SOC_PR* representing SOC stocks and stock changes in the project scenario. So Equation 16 is used to calculate the parameter:

  $\Delta C_{SOC\_PROJ,t}$ Change in carbon stock in soil organic carbon under the project scenario within the project area in year t (t CO_2e)

5.2.3 Estimating Actual Project Removals in SOC With Validated Model Predictions

Process-based modelling of actual SOC stock change in the project scenario follows the procedures in Section 5.2.2, with the following modifications:

- Simulations are run based on actual management activities as implemented in the project scenario.

- SOC models must be validated at least every five years using direct in-situ measurements of SOC stocks at sample points taken within the project area, following the guidance for model validation in **PT003** to ensure the model is appropriately simulating SOC stock changes and error is sufficiently accounted for.
- Projects must follow the sampling design guidance and requirements in Section 5.1.1.1 to select the sample points for in-situ measurements and requirements in Section 5.1 for measuring SOC at sample points.

5.3 Conservative Default Values

Conservative default values can be used to estimate changes in SOC stocks in the baseline scenario and expected changes in SOC stocks in the project scenario. Procedures for estimating initial SOC stocks, identifying appropriate default values for SOC change, and calculating change in SOC stocks are described below.

5.3.1 Estimating Initial SOC Stocks

Projects estimate initial SOC stocks at t_0 by:

a. Applying the direct measurement guidance and requirements in Section 5.1;
b. Extracting predicted values at sample points within the project area from digital soil maps, regional/national soil databases, or similar datasets; or
c. Selecting reference SOC stock values from Table 2.3 in Chapter 2, Volume 4 of the IPCC 2019 Refinement to the 2006 IPCC Guidelines. The reference value must then be adjusted according to the IPCC default factors for $F_{h,LU}$, $F_{h,MG}$, and $F_{h,I}$ representative of the baseline land use, management, and input characteristics to estimate SOC stocks at t_0. When using such defaults, the project proponent should provide evidence that the initial SOC stocks in the baseline scenario can reasonably be expected to align with reference values for the relevant climate zone and soil type, after adjusted using the default factors $F_{h,LU}$, $F_{h,MG}$, and $F_{h,I}$.

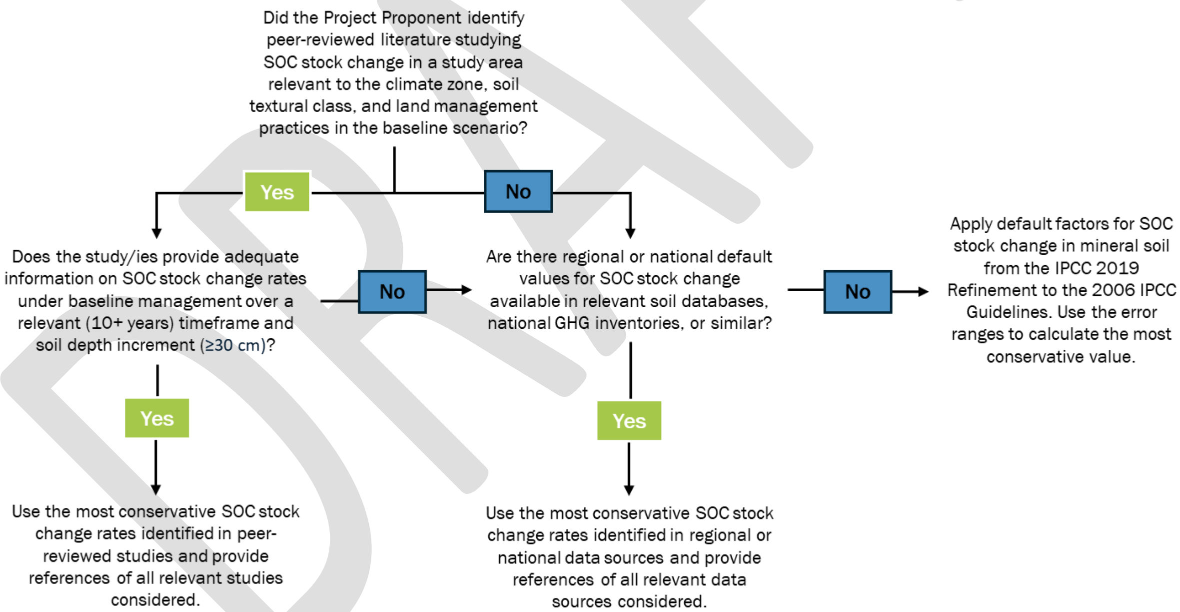
If applying approach a or b above, average SOC at t_0 is calculated with Equation 10.

Where the baseline scenario or project scenario exhibits a range in climate zones, soil types, land uses, management practices, and/or inputs, the project area should be stratified and relevant t_0 SOC stock and default stock change factor(s) applied to each stratum.

5.3.2 Identifying Appropriate Conservative Default Values

The following decision tree should be applied to select appropriate conservative default values:

1) Projects shall identify whether peer-reviewed literature exists that provides validated SOC sequestration rates specific to the project's geographic region, land use, and management practices and over relevant soil depths and time frames. When such literature is available, proponents must provide the reference(s) and justify its applicability and conservativeness.
2) In the absence of peer-reviewed literature, project proponents should assess the availability of validated default values from regional soil databases, national greenhouse gas assessments, or similar. These regional or national default values must be documented with evidence demonstrating their appropriateness for project conditions, validation status, and adherence to conservative principles.
3) Where regional or national values are unavailable, project proponents may apply IPCC default values using default reference SOC values and SOC stock change factors ($F_{h,LU}$, $F_{h,MG}$, and $F_{h,I}$) for the relevant land use scenario provided in IPCC 2019 Refinement to the 2006 IPCC Guidelines.



The default factor must be relevant to project timeframes (10+ years) and soil depths of ≥30 cm. The depth to which SOC stocks and stock change are determined in the baseline scenario must match that used in the project scenario.

Where more than one default value or a range of values is identified–or where error ranges are available–the project must apply the most conservative value available (i.e., the value in the identified range of possibilities for which the baseline gains the most SOC or loses the least SOC).

A project may apply a zero-change baseline if the most conservative default value identified following the steps above indicates that the baseline would lose SOC over time.

5.3.3 Calculating Change in SOC

$\Delta C_{SOC\_BSL,t}$ Change in carbon stock in soil organic carbon under the baseline scenario within the project area in year t (t CO_2e)

$\Delta C_{SOC\_PROJ,t}$ Change in carbon stock in soil organic carbon under the project scenario within the project area in year t (t CO_2e)

To calculate annual change in SOC stocks in year t of the current verification period using conservative defaults, the time period over which those defaults apply must be integrated into the calculations. Most IPCC default factors represent the change in SOC stocks over a 20 year period. For IPCC default values, change in carbon stock under the baseline or project scenario in year t (i.e. $\Delta C_{SOC\_BSL,t}$ or $\Delta C_{SOC\_PROJ,t}$) is calculated with Equation 17 to Equation 19.

$$\Delta C_{SOC,t} = \sum_{h=1}^{H} \Delta SOC_{i,t} \times A_i$$

Equation 17

Where:

$\Delta SOC_{i,t}$ Change in SOC stock in stratum *i* in year t (tCO_2e/ha/yr; see Equation 18)

A_i Extent of stratum *i* (hectares)

H Number of strata

$$\Delta SOC_{i,t} = \frac{SOC_{i,final} - SOC_{i,t0}}{T}$$

Equation 18

Where:

$\Delta SOC_{i,t}$ Change in SOC stock in stratum *i* in year t (tCO_2e/ha/yr)

$SOC_{i,final}$ SOC stock in stratum *i* at the end of the crediting period (tCO_2e/ha; see Section 5.3.2)

$SOC_{i,t0}$ SOC stocks in stratum *i* in the first year of the project, t_0 (tCO_2e/ha; see Section 5.3.1)

T Duration of the crediting period (years)

Final SOC stocks derived from IPCC default values are calculated as:

$$SOC_{i,final} = SOC_{i,t0} \times F_{i,LU} \times F_{i,MG} \times F_{i,I}$$

Equation 19

Where:

$SOC_{i,final}$ SOC stock in stratum *i* at the end of the crediting period (tCO_2e/ha)

$SOC_{i,t0}$ SOC stocks in stratum *i* in the first year of the project, t_0 (tCO_2e/ha; see Section 5.3.1)

$F_{h,LU}$ Default factor for SOC stock changes in stratum *i* attributable to baseline land use over time *T* (unitless)

$F_{i,MG}$ Default factor for SOC stock changes in stratum *i* attributable to baseline management practices over time *T* (unitless)

$F_{i,I}$ Default factor for SOC stock changes in stratum *h* attributable to baseline inputs over time *T* (unitless)

If IPCC defaults factors for SOC stock change are not used and instead a conservative default value is derived from literature or alternative source, the default factor would capture the aggregate impact of land use, management, and inputs on SOC stocks in a single value. Thus, instead of default values for $F_{h,LU}$, $F_{h,MG}$, and $F_{h,I}$, the conservative default value represents $\Delta SOC_{i,t}$

5.4 Uncertainty

Uncertainty calculations depend on the approach used to estimate the baseline and project scenario SOC stock changes:

- Where direct measurements are used, uncertainty must account for sampling error following the procedures in **PU005** Section 5.1.1. Measurement error is assumed to be zero provided QA/QC procedures in field and laboratory procedures are applied.
- Where process-based modelling is used, uncertainty is the sum of both sampling error and model prediction error. Sampling error captures error from only a portion of the area being sampled and subsequently modelled. Model prediction error captures error and

uncertainty in model parameters and overall model structure. Measurement error is assumed to be zero provided QA/QC procedures in field and laboratory procedures are applied. The sum of sampling error and model prediction error is calculated with Equation 20.

- Where conservative defaults are used, uncertainty is assumed to be zero since the most conservative default values must be used.

$$U_x = \sqrt{U_{x,sample}{}^2 + U_{x,model}{}^2}$$

Equation 20

Where:

U_x Combined sample and model uncertainty of carbon stock estimate x at a 90% confidence level (percent)

$U_x, sample$ Sample uncertainty of carbon stock estimate x at a 90% confidence level (percent; see **PU005** Section 5.1.1)

$U_{x,model}$ Model uncertainty of carbon stock estimate x at a 90% confidence level (percent; see **PT003** Equation 2)

6 Parameters

Data/Parameter	S
Units	tCO_2e
Description	Standard deviation of the SOC stock change between t_0 and t_x
Equations	Equation 1, Equation 2
Source	Calculated from measurements in a pilot study, or estimated based on previous studies under similar conditions to the project area.
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Pilot studies or existing studies under similar conditions to the project areas provide an indication of variability carbon stock change.

Purpose of Data	Determining the minimum number of samples needed to directly measure changes in SOC stocks.
Comments	NA

Data/Parameter	t_α
Units	Unitless
Description	Two-sided critical value of the t-distribution at a given significance level (α)
Equations	Equation 1, Equation 2
Source	NA
Value	Frequently taken as 0.05 (5%)
Justification of choice of data or description of measurement methods and procedures applied	Defines the required significance level for detecting a change.
Purpose of Data	Determining the minimum number of samples needed to directly measure changes in SOC stocks.
Comments	NA

Data/Parameter	t_β
Units	Unitless
Description	One-sided quartile of the t-distribution corresponding to a probability of type II error β
Equations	Equation 1, Equation 2
Source	NA
Value	E.g. 90%
Justification of choice of data or description of measurement methods and procedures applied	Defines the required significance level for detecting a change.
Purpose of Data	Determining the minimum number of samples needed to directly measure changes in SOC stocks.

PLAN VIVO

Comments	NA

Data/Parameter	$wet\ mass$
Units	g
Description	Mass of the subsample collected prior to oven drying
Equations	Equation 3
Source	Laboratory analysis of soil samples
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Laboratory analysis following procedures in Section 5.1.2 allows for accurate estimation of wet mass of soil samples.
Purpose of Data	Estimation of gravimetric water content of soil samples.
Comments	NA

Data/Parameter	$dry\ mass$
Units	g
Description	Mass of the subsample collected after oven drying
Equations	Equation 3
Source	Laboratory analysis of soil samples
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Laboratory analysis following procedures in Section 5.1.2 allows for accurate estimation of dry mass of soil samples.
Purpose of Data	Estimation of gravimetric water content of soil samples.
Comments	NA

Data/Parameter	$mass_{air-dried}$
Units	g

Description	Mass of the full sample after air drying
Equations	Equation 4
Source	Laboratory analysis of soil samples
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Laboratory analysis following procedures in Section 5.1.2 allows for accurate estimation of dry mass of soil samples.
Purpose of Data	Estimation of dry mass of soil samples.
Comments	NA

Data/Parameter	π
Units	Unitless
Description	Mathematical constant that represents the ratio of a circle's circumference to its diameter
Equations	Equation 5
Source	Mathematical constant
Value	Approximately equal to 3.142
Justification of choice of data or description of measurement methods and procedures applied	NA
Purpose of Data	Estimation of volume of soil samples
Comments	NA

Data/Parameter	D
Units	cm
Description	Diameter of the sample tool, e.g., core or auger
Equations	Equation 5
Source	Measured during soil sampling
Value	NA

Justification of choice of data or description of measurement methods and procedures applied	Diameter of each tool used for soil sampling e.g. core or auger must be measured.
Purpose of Data	Estimation of volume of soil samples
Comments	NA

Data/Parameter	$length; length_{i,p,d}$
Units	cm
Description	Length of the sample depth increment *d* for sample point *p* in stratum *i*
Equations	Equation 5; Equation 8; Equation 9
Source	Measured during soil sampling
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Length of sample depth of each tool used for soil sampling e.g. core or auger must be measured.
Purpose of Data	Estimation of volume of soil samples
Comments	NA

Data/Parameter	$mass_{coarse\ frags}$
Units	g
Description	Mass of coarse fragments >2 mm collected after sieving
Equations	Equation 6
Source	Laboratory analysis of soil samples
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Laboratory analysis following procedures in Section 5.1.2 allows for accurate estimation of dry mass of soil samples.

Purpose of Data	Calculating corrected volume of soil samples.
Comments	NA

Data/Parameter	$OC_{i,p,d}$
Units	g/kg
Description	Soil organic carbon content in stratum *i* at sample point *p* within sample depth layer *d*
Equations	Equation 8
Source	Soil organic carbon concentration analysis via dry combustion, spectroscopy, or SOM analysis (see Section 5.1.2.4)
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Dry combustion, spectroscopy, and SOM analysis following the procedures in Section 5.1.2 are established methods for estimating SOC concentration.
Purpose of Data	Estimating SOC stock from a soil sample.
Comments	NA

Data/Parameter	A_i
Units	ha
Description	Extent of project area in stratum *i*
Equations	Equation 15, Equation 17
Source	Boundary maps of project areas
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Calculated as the sum of the extent of all project areas within a given stratum.
Purpose of Data	Scaling stratum level SOC stock estimates to the project area level

Comments	NA

Data/Parameter	$SOC_{i,t0}$
Units	tCO_2e/ha
Description	SOC stocks in stratum *i* in the first year of the project, t_0
Equations	Equation 18, Equation 19
Source	Direct measurements; digital soil maps; regional/national soil databases, or similar datasets; or reference SOC stock values from Table 2.3 in Chapter 2, Volume 4 of the IPCC 2019 Refinement to the 2006 IPCC Guidelines.
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	Direct measurements, existing datasets and conservative default values can be used to estimate carbon stocks at a given location.
Purpose of Data	Estimating change in SOC stocks over the crediting period.
Comments	NA

Data/Parameter	$F_{i,LU}$
Units	Unitless
Description	Default factor for SOC stock changes in stratum *i* attributable to land use over time *T*
Equations	Equation 19
Source	IPCC 2019 Refinement to the 2006 IPCC Guidelines
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	IPCC Guidelines provide default factors for SOC stock changes under a range of land use types.
Purpose of Data	Estimation of SOC stocks at the end of the crediting period.
Comments	NA

Data/Parameter	$F_{i,MG}$
Units	Unitless
Description	Default factor for SOC stock changes in stratum *i* attributable to management practices over time *T*
Equations	Equation 19
Source	IPCC 2019 Refinement to the 2006 IPCC Guidelines
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	IPCC Guidelines provide default factors for SOC stock changes under a range of management practices.
Purpose of Data	Estimation of SOC stocks at the end of the crediting period.
Comments	NA

Data/Parameter	$F_{i,I}$
Units	Unitless
Description	Default factor for SOC stock changes in stratum *h* attributable to inputs over time *T*
Equations	Equation 19
Source	IPCC 2019 Refinement to the 2006 IPCC Guidelines
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	IPCC Guidelines provide default factors for SOC stock changes under a range of inputs.
Purpose of Data	Estimation of SOC stocks at the end of the crediting period.
Comments	NA

Data/Parameter	$U_x, sample$
Units	percent

Description	Sample uncertainty of carbon stock estimate x at a 90% confidence level
Equations	Equation 20
Source	**PU005** Section 5.1.1
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	See **PU005** Section 5.1.1
Purpose of Data	Estimating combined sample and model uncertainty of carbon stock estimate x at a 90% confidence level
Comments	NA

Data/Parameter	$U_{x,model}$
Units	percent
Description	Model uncertainty of carbon stock estimate x at a 90% confidence level
Equations	Equation 20
Source	**PT003** Equation 2
Value	NA
Justification of choice of data or description of measurement methods and procedures applied	See **PT003** Section 5.3.5
Purpose of Data	Estimating combined sample and model uncertainty of carbon stock estimate x at a 90% confidence level
Comments	NA

7 References

Aynekulu, E., Vagen, T-G., Shephard, K., Winowiecki, L. 2011. A protocol for modeling, measurement and monitoring soil carbon stocks in agricultural landscapes. Version 1.1. World Agroforestry

Centre, Nairobi. https://www.cifor-icraf.org/publications/downloads/Publications/PDFS/TM11192.pdf

DCCEEW 2024, Supplement to the Carbon Credits (Carbon Farming Initiative – Estimation of Soil Organic Carbon Sequestration using Measurement and Models) Methodology Determination 2021, Department of Climate Change, Energy, the Environment and Water, Canberra, October. CC BY 4.0.

FAO. 2019. Measuring and modelling soil carbon stocks and stock changes in livestock production systems: Guidelines for assessment (Version 1). Livestock Environmental Assessment and Performance (LEAP) Partnership. Rome, FAO. 170 pp. Licence: CC BY-NC-SA 3.0 IGO. https://openknowledge.fao.org/server/api/core/bitstreams/3573cc7c-f8b0-42cc-bead-ea56c502647e/content

FAO. 2020. A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes – GSOC-MRV Protocol. Rome. https://doi.org/10.4060/cb0509en

Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007 May;39(2):175-91. doi: 10.3758/bf03193146. PMID: 17695343.

Ferchaud, F., Chlebowski, F., & Mary, B. (2023). SimpleESM: R script to calculate soil organic carbon and nitrogen stocks at Equivalent Soil Mass (Doctoral dissertation, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement (INRAE)).

Gruijter, J. J. de, A. B. McBratney, B. Minasny, I. Wheeler, B. P. Malone, y U. Stockmann. «Farm-Scale Soil Carbon Auditing». Geoderma 265 (2016): 120-30. https://doi.org/10.1016/j.geoderma.2015.11.010.

Haden, A. C.; Yang, W. H.; DeLucia, E. H. Soils' Dirty Little Secret: Depth-based Comparisons Can Be Inadequate for Quantifying Changes in Soil Organic Carbon and Other Mineral Soil Properties. Glob Change Biol 2020, 26 (7), 3759–3770. https://doi.org/10.1111/gcb.15124.

IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Published by the Published by the Intergovernmental Panel on Climate Change. ISBN 978-4-88788-232-4. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

McBratney, Alex B., and Budiman Minasny. "Comment on "Determining soil carbon stock changes: Simple bulk density corrections fail"[Agric. Ecosyst. Environ. 134 (2009) 251–256]." Agric Ecosyst Environ 136.12 (2010): 185-6.

PM001 Agriculture and Forestry Carbon Benefit Assessment Methodology. Version 1.0. Available from: https://www.planvivo.org/projects/certify-a-project/pvclimate/methodologies/approved-methodologies

PT003 Guidance for the use of models validated with measurements in PV Climate projects. Version 1.0. Available from: https://www.planvivo.org/projects/certify-a-project/pvclimate/methodologies/approved-tools

PU001 Estimation of Baseline and Project GHG Removals by Carbon Pools in Plan Vivo Projects, Version 1.2. PV Climate Module. Available from: https://www.planvivo.org/projects/certify-a-project/pvclimate/methodologies/approved-modules

PU005 Estimation of uncertainty of carbon benefit estimates in Plan Vivo projects. Version 1.1. Available from: https://www.planvivo.org/projects/certify-a-project/pvclimate/methodologies/approved-modules

PV Climate Glossary. Version 1.1. Available from: https://www.planvivo.org/projects/certify-a-project/pvclimate/documents

Sharma, Sumit, Tracy Wilson, Tyson Ochsner, y Jason G. Warren. «Sampling Probes Affect Bulk Density and Soil Organic Carbon Measurements». Agricultural & Environmental Letters 5, n.o 1 (2020): e20005. https://doi.org/10.1002/ael2.20005.

Vågen, T.-G., & Winowiecki, L. A. (2023). The Land Degradation Surveillance Framework (LDSF): Field manual for land and soil health assessments [PDF]. Center for International Forestry Research & World Agroforestry (CIFOR-ICRAF). https://www.cifor-icraf.org/publications/pdf/flyer/LDSF-Field-Manual.pdf

Rossel, R.V., Behrens, T., Ben-Dor, E., Brown, D.J., Demattê, J.A.M., Shepherd, K.D., Shi, Z., Stenberg, B., Stevens, A., Adamchuk, V. and Aïchi, H., 2016. A global spectral library to characterize the world's soil. *Earth-Science Reviews*, *155*, pp.198-230. https://doi.org/10.1016/j.earscirev.2016.01.012

Wendt, J. W.; Hauser, S. An Equivalent Soil Mass Procedure for Monitoring Soil Organic Carbon in Multiple Soil Layers. European Journal of Soil Science 2013, 64 (1), 58–65. https://doi.org/10.1111/ejss.12002

Appendix 1 Summary of Compliance with PV Climate Methodology Requirements

Methodology Requirement Type	Summary of Compliance
1.1 Methodology Structure	The tool is prepared using the latest template provided by Plan Vivo.
1.2 Uncertainty	See Section 5.4: • Following the procedures in **PU005** Section 5.1.1. Measurement error is assumed to be zero provided QA/QC procedures in field and laboratory procedures are applied. • Where process-based modelling is used, uncertainty is the sum of both sampling error and model prediction error. The sum of sampling error and model prediction error is calculated with Equation 20. Where conservative defaults are used, uncertainty is assumed to be zero since the most conservative default values must be used.
1.3 Quantifying Emissions and Removals	• The tool is used to quantify changes in soil organic carbon stocks. • All procedures are consistent with international good practices in greenhouse gas accounting. All data, parameters, assumption and calculations must be fully described and justified.
1.4 Measurements and Sampling	All procedures that involve measurements apply established approaches for sample collection and analysis that minimise measurement error (see Section 5.1.1).
1.5 Models, Default Factors and Proxies	• If process-based models are used, it must be demonstrated that models have been appropriately calibrated to the project conditions, models must be applied in a manner that minimises potential for over-estimation of carbon benefits (See Section 5.2). • All default values used are sourced from reliable peer-reviewed literature that is appropriate to the scope of application (see Section 5.3).

	Proxy values can only be used if there is robust evidence that they are strongly correlated to the parameter they represent.
2.1 Applicability Conditions	• Applicability conditions are described in Section 4.
2.2 Carbon Pools and Emission Sources	• The tool is applicable to projects where soil organic carbon has been identified as a significant carbon pool following the procedures in an approved methodology.
2.3 Baseline Scenario and Additionality	• The tool must be applied within an approved methodology that includes procedures for describing the baseline scenario and demonstrating additionality.
2.4 Carbon Baseline	• The tool describes approaches for estimating annualised baseline removals in soil organic carbon, based on the identified baseline scenario. • The tool can be applied to update carbon baselines.
2.5 Project Emissions and Removals	• The tool describes approaches for estimating annual removals in soil organic carbon under the project scenario. • The tool includes indicators and procedures for estimating project removals in each verification period.
2.6 Harvesting	• The tool is not applicable to harvesting.
2.7 Leakage	• The tool must be applied within an approved methodology that includes procedures for accounting for leakage.
2.8 Calculation of Carbon Benefits	• The tool must be applied within an approved methodology that includes procedure for calculation of carbon benefits.