Soil Sampling and Testing (MRV requirements)

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1. Background

The purpose of this document is to describe the minimum requirements for soil sampling and testing to determine the soil organic carbon (SOC) stocks within a defined land area within the UK.

This document covers the following deliverables/activities:

- The site selection, sampling design and parameters.
- The sampling methodology and analytical methods.
- Results, calculations and reporting.

This document is intended to provide a set of minimum standards for soil sampling and soil testing that is used by the UKCCC, equivalent methodologies may be applied to projects subject to the approval of UKCCC. Existing client data must be submitted by the project developer to the UKCCC for approval to ensure compliance with The Standard.

2. Scope/Objective

This document outlines methods and practices for the calculation of soil organic carbon stocks, particularly focussed on the measurement of change in carbon stock over a period of time.

This document is applicable to agricultural and amenity land that is being managed as:

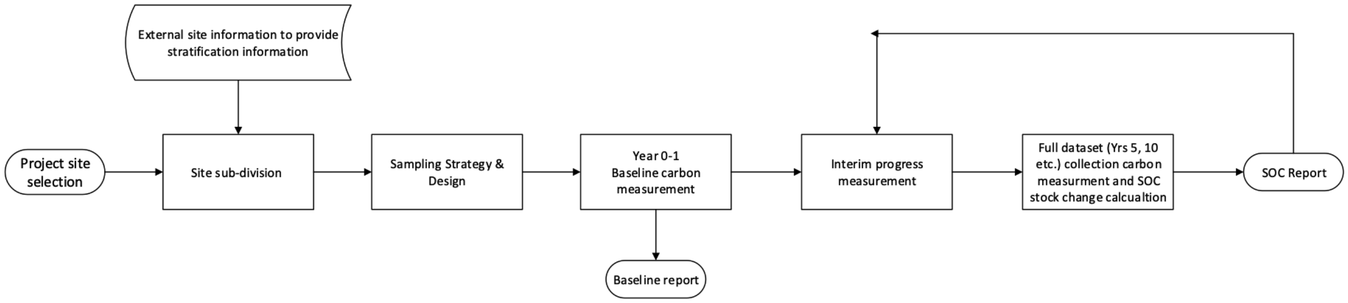
- part of an arable rotation,
- permanent cropland (including vineyards and orchards),
- permanent pasture, grassland or herbal ley,
- temporary grassland or leys,

and is managed with practices that maintain and enhance soil health, the below ground carbon stocks and generally improve the land’s biodiversity and eco-system function. Assessment of above ground carbon accrual is described elsewhere.

Land that is classified as peatland, as described in the Peatland Carbon code [1], is not applicable to this document. Woodland, agroforestry, and silvopasture systems may be applicable to this document, and the UKCCC in general.

The process requirements described are intended to be applied to a multi-year project on a defined land area. A comprehensive baseline dataset is created at the start of the project and another full dataset gathered at defined time periods (typically every 3-5 years) during the project’s lifecycle, to allow the accumulation of soil organic carbon calculated during the project. Furthermore, it would be anticipated that further interim datasets may be collected between the fixed timepoints to track progress of soil carbon accumulation, however normally these datasets would not be used as part of the formal project delivery.

The process may defined in a number of sequential steps:



This document does not cover methodologies for the interim progress monitoring, shown in the process flow diagram.

At this point the UKCCC does not provide example Standard Operating Procedures (SOPs) for the requirements described in Sections 4 -6, projects submitted to the UKCCC for accreditation should include outline SOPs to ensure the project meets the requirements described within.

The increase of soil organic carbon stock for an enterprise may be converted into carbon credits after the enterprise has reached, and has been accredited as, carbon Net Zero.

3. Terms, and Acronyms

Acronyms and specialist terms used in this document are defined below.

3.1. Terms

Carbon dioxide equivalent (CO_2e)	The number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas
Residual soil Organic Carbon (ROC)	The residual soil organic carbon fraction that is measured at an oven temperature of 600°C when analysis follows BS EN 17505:2023 analytical methodology. SOC is the summation of TOC_{400} and ROC.
Rock Fragment	Pieces of rock (that do not pass through a 2mm sieve, but smaller than 10mm) that are to be accounted for in calculation of bulk density.
Stratification	The division of an area into smaller sub-areas based around a variable that will be reasonable homogeneous across the sub-area based on a selected parameter. The approach should be repeatable across the project area (landscape).
TOC_{400}	The soil organic carbon fraction that is measured at an oven temperature of 400°C when analysis follows BS EN 17505:2023 analytical methodology. SOC is the summation of TOC_{400} and ROC.

3.2. Acronyms

ESM	Equivalent Soil Mass
FAO	Food and Agriculture Organization of the United Nations
FD	Fixed depth *(soil bulk density)*
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LoI	Loss on Ignition
MDD	Minimal Detectable Difference
NDVI	Normalized Difference Vegetation Index
RPA	Rural Payments Agency
SBD	Soil Bulk Density
SCS	Soil Organic Carbon Stock
SIC/ TIC	Soil/Total Inorganic Carbon
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SOP	Standard Operating Procedure
TC	Total Soil Carbon
UKCCC	UK Carbon Code of Conduct

4. Site Selection & Sub-division.

Soil has both spatial and depth variability and as such this leads to challenges in the measurement of change SOC across a selected area. To help in providing meaningful results from a series of measurements a number of strategies should be employed. Firstly, the project requires a sufficient number of samples (data points) to be able to observe changes in statistically relevant manner. One of the variables affecting the required number of samples is the degree of variation within the sample set, stratification of the whole area into smaller parcels with similar soil characteristics should be used to reduce the variation over a whole site.

4.1. Site Selection

Any project requires a fixed area for the duration of the project along with an agreed depth profile that will create the total soil volume included in the project. Unless restricted by soil Horizon C or the bedrock (Horizon R) the project depth should be at least 60cm [2]. The depth selected across a whole project area should be constant, unless restricted by Horizons C and/or R. Note, to ensure the most accurate assessment of changes across the project period the project design should express results in terms of Equivalent Soil Mass (ESM) and thus the selected depth is indicative only.

A project area shall be recorded on a GIS map to provide an accurate estimate of the project area, and to ensure the complete project area will undergo land management practices that favour the increase of stored carbon, which should apply to both above ground and below ground increases. At this point areas within the defined area that will not be actively managed or unsuitable (e.g. roads, track, hardstanding's etc.), should be highlighted and excluded from the project design. Notwithstanding non-managed areas the project area would normally be contiguous, if the proposed project area comprises "islands" these should only be accepted if the "islands" are of similar soil type and managed in the same manner as the main block of land.

4.2. Sites with Multiple Management Responsibility

It is possible that a project site may be comprised of multiple properties (a Group) as the combination of properties may result in a more cost-effective sampling regime through more efficient stratification over a larger areas and efficiencies gained through shared administrative costs.

For a project to comprise a Group several criteria need to be satisfied across the total area:

- Comparable soil types,
- Similar land characteristics and usage,
- Consistent management practices across those with management responsibility.
- A formal agreement between parties to underpin the project for its proposed lifetime.

4.3. Site Sub-division

In order to attempt to minimise spatial variability across the project area some stratification is necessary to define sub-areas where the soil's ability to hold and alter its carbon content is relatively similar. This might include parameters such as:

- Soil type
- Topography/ Vegetative Cover/ Boundaries
- Land use (current and/or historic)
- Land management practice

4.3.1. Stratification by Soil Type

The most straightforward stratification of a site is by soil type, overlaying a UK soil type map (such as the Cranfield NATMAP Vector soil database [3]) over the project area allows a rapid assessment of soil types and the definition of sub-areas. Published soil maps often have multiple layers which allow different classifications of the soils to be considered such as soil texture, composition, pH, soil organic carbon content, etc.

Some of the map layers are built by interpolation from a limited number of a ground-truthed data points and care maybe needed as the boundary lines between soil groups may not provide accurate information for a particular project area. Physical inspection and local knowledge (e.g. from landowner, or agronomist) may be used to refine sub-area boundaries, in some cases in-field assessment may be necessary to redefine the sub-area to align with actual observations.

4.3.2. Stratification by Topography/ Vegetative Cover/ Boundaries

Further levels of stratification can be considered as part of the project sampling design.

The topography of a site may also affect SOC levels, although land slope itself, below *ca.* 10°, does not seem to have a great influence on SOC [4] although land with steeper slopes, the slope has an effect on SOC levels which may be mainly due to the enhanced potential for soil erosion on steeper ground [5]. Notwithstanding the inherent slope of the land, the aspect of the slope has also been found to be influential.[4], [6], [7], [8]

For more "natural" areas, a measure of vegetative cover using the Normalized Difference Vegetation Index (NDVI) which is a ratio of the difference between near infrared and red reflectance to the sum of near infrared and red reflectance can be a stratification parameter [5] The NDVI is closely related to vegetation cover, biomass and the leaf area index.

Vegetative boundaries, hedges and tree lines, have a well-documented local effect on SOC levels [9], [10], [11], [12], [13], in contrast to abiotic boundaries such as fence lines or walls [13] Including this potential stratification may prove challenging owing to the linear nature which may make any sampling plan complex.

4.3.3. Stratification by Land Use

Consideration may also be afforded to the planned, over the lifespan of the project, (or historic) land use for a project area. In many cases project areas may be defined by an existing field system and for the point of view of reporting granular results the fields provide a useful and identifiable structure.

For the purpose of area stratification if, over the 5-year period of a project, the land management practice of adjacent fields is identical then multiple fields may be considered as a single sampling zone. Conversely, in arable systems, if management practices differ within the field boundaries then each management area could be considered as an individual sampling zone.

Additionally, if there has been a significant, recent, change in land use for an area this should also be a consideration as the historic (baseline) SOC values may be heavily influenced by the previous land use.

5. Sampling Strategy and Design

5.1. Sampling Design

Sampling philosophy for UKCC projects may be either design based, or model based but it should provide a design that optimises spatial coverage. For example, a simple random sampling pattern may be adopted, or if more cost effective, a randomised grid sampling pattern may be used.

5.2. Sampling Strategy

The essential key to any sampling strategy is to ensure that sampling and the subsequent testing provides a data set that can provide a statistical meaningful value for the SOC content in each of the sub-area. In general, the greater number of samples the greater the statistical power to measure change in SOC over the project period.

To aid the development of the full sampling plan a preliminary sampling (and testing) survey may be undertaken to gain understanding of the SOC variation over the project site.

5.2.1. Minimum Sampling Parameters

Wherever possible, for any chosen parcel, regardless of other statistical factors, a minimum of 10 cores should be collected. In cases where compositing is part of the sample collection strategy this should equate to a minimum of 2 composite samples.

5.2.2. Statistical Considerations

The sampling strategy should aim to provide a data set for each sub-area where the soil organic carbon stock (SCS) is calculated that provides a standard deviation with a confidence interval < ± 10% (at a confidence of 90%).

For the purposes of the statistical analysis the sub-area over which a SCS is calculated comprises a number of discrete parcels that may be combined as part of the stratification considerations. However, it would normally be expected that the project report includes results at an individual parcel level.

If for a sub-area the confidence interval is > ± 10% (at a confidence of 90%) then consideration should be given to modify the sampling strategy either through modification of the stratification approach or increasing the number of cores (samples) collected. This may be estimated following the equation presented in VCS Module VDM0021: Estimation of Stock in the Soil Carbon Pool [14]:

$$n_{rev} = t^2 \times s^2 \times \left(\frac{1}{0.1 \times \bar{X}}\right)^2 \qquad \text{(Eq. 1)}$$

Where:

n_{rev}	is the revised estimate of cores (samples) required,
t	is the Student *t*-test 0.90 values for *n-1*, with *n* being the number of cores (samples) already collected,
s	is the Standard Deviation of the existing relevant sample data set,
$\bar{X}$	is the Mean value for the SOC in the existing relevant sample data set.

If, normally for the proposes of cost control, including additional sampling points is not viable then a "discounted" SCS may be calculated to reflect the reduction in confidence interval. Again, following the methodology presented in VCS Module VDM0021: Estimation of Stock in the Soil Carbon Pool [14]:

For a baseline measurement:

$$SCS_{a\prime} = SCS_a \times \left(1 + (CI - 0.1)\right)$$

For calculations later in the project :

$$SCS_{a\prime} = SCS_a \times \left(1 - (CI - 0.1)\right)$$

Where:

$SCS_{a\prime}$	is the revised soil organic carbon stock value for area, *a*,
SCS_a	is the base calculated value of soil organic carbon stock value for area, *a*,,
CI	Is the calculated confidence interval (at 90% confidence)

6. Initial (Baseline) Soil Carbon Measurement

6.1. Field Sampling

The field sampling should be guided by the sampling design, each sampling location shall be geo-located by either GPS coordinates or its unique What3Words reference.

6.1.1. Sampling Depth

Historically, SOC measurements have been taken between 0-30cm aligning with the IPCC [15] and global assessments of soil carbon are usually reported with respect to the 0-30cm horizon (e.g. Global assessment of soil carbon in grasslands – From current stock estimates to sequestration potential[16]). This is despite *ca.* 50% of SOC being located below 30cm [17], [18], [19]. More recently the FAO has suggested sampling to depths greater than 30cm should be adopted, where the soil depth is greater than 30cm[20], with best practices suggested to be sampling to 60cm [2].

To ensure the majority of carbon stocks are assessed a minimum depth of 60cm (or to Horizon C, if less than 60cm) is required. Sampling greater than 60cm, typically to 1m, is encouraged where possible.

6.1.2. Sample Collection

Collecting multiple samples >30cm generally makes use of mechanical collection (as opposed to hand digging/auguring) which is usually based around a vibratory-hammer coring unit, which shall provide a continuous soil profile from the soil surface to full profile depth. Wherever possible the collected profile should be sub-divided into, a minimum, of 3 consistent depth intervals. The chosen sub-divisions should, if possible, be consistent across the project but must be identical across each sampling parcel. Typically for soil depths greater than 60cm the selected sub-divisions might be either: 0-30cm, 30-60cm, 60+cm (this latter division may be to the maximum probe depth or a fixed depth selected prior to sampling) or 0-15cm, 15-30cm, 30-60cm.

Multiple soil cores may be collected from a single sample location and composited by depth interval to smooth spatial variability of SOC and reduce project costs. If compositing is undertaken at least 5 cores should be combined to create the composite [21].

Where expertise allows soil cores may be sub-divided by soil horizon (e.g. as described in the NRCS Field Book for Describing and Sampling Soils[22]). Major soil horizons should not be combined as they may contain significantly different SOC concentrations. However, a single horizon may be further divided by depth to provide at least 3 sub-divisions.

6.1.3. Sample Collection – Soil Bulk Density

To obtain a value for the carbon stock with the soil a measure of the bulk density of the soil is required in addition to the SOC concentration. The accurate measurement of the soil bulk density (SBD) requires the collection of an undisturbed soil core at each sampling location. The undisturbed core must be from the same or immediately adjacent location as the soil sample to be analysed for carbon content. This approach potentially has a number of issues, the sampling probe diameter can introduce bias into the calculation of SBD through the potential to compress the sample whilst inserting the probe [23], [24], and the requirement for an undisturbed core for analysis preclude the ability to composite samples. Having noted those issues, the use of SBD values in the calculation is still acceptable in the calculation of the SCS.

As an alternative, and the preferred, method for the calculation of SCS an ESM approach may be adopted. ESM does not require an accurate value of SBD to be collected and thus is applicable to composite samples.

6.2. Soil Organic Carbon Analysis

This protocol requires SOC to be measured using a methodology based upon Dumas dry combustion analysis [25]. Measurements derived from Loss of Ignition (LoI) [26] or Walkley-Black methodologies [27] are not accepted.

A number of international standards have been published that describe SOC analysis based on Dumas dry combustion analysis:

BS 7755-3.8:1995 Soil quality. Chemical methods - Determination of organic and total carbon after dry combustion (elementary analysis)

BS ISO 23400:2021 Guidelines for the determination of organic carbon and nitrogen stocks and their variations in mineral soils at field scale

BS EN 15936:2022 Soil, waste, treated biowaste and sludge. Determination of total organic carbon (TOC) by dry combustion

BS EN 17505:2023 Soil and waste characterization. Temperature dependent differentiation of total carbon (TOC400, ROC, TIC900)

A methodology based on any of these standards shall be applicable.

The methodology used should ensure the soil is prepared to provide a <2mm representative (fine soil) fraction that has been suitably dried. In addition to reporting the SOC concentration of the soil, the soil inorganic carbon (SIC) concentration (and total carbon (TC)) should be measured and reported.

6.3. Soil Bulk Density Evaluation

If a SBD value is to be used in the calculation of the soil carbon stocks then it should account for any rock fragments within the soil. Rock fragments within the soil reduce the volume of the soil which actually has SOC storing capacity and thus can lead to an overestimation of soil carbon stock [28]. This overestimation is not significant for <5% rock fragments [29] but above 5% the soil carbon stock calculation should be related to the fine soil (<2mm) bulk density measure and account for the proportion of rock fragments.

Total Bulk Density: $$\rho_{total} = \frac{Weight_{total}}{Volume_{sample}} \quad \text{(Eq. 2)}$$

Fine Soil Bulk Density: $$\rho_{fine} = \frac{Weight_{total} - Weight_{rock}}{Volume_{sample} - Volume_{rock}} \quad \text{(Eq. 3)}$$

Measures of bulk density from disturbed soil samples are **not** permitted unless part of an ESM calculation.

6.3.1. Fixed Depth Bulk Density *vs*. Equivalent Soil Mass

Evidence suggests that over the lifetime of a soil carbon project a change in the soil bulk density can occur owing to changes in farming practice during the duration of the project. Calculation of SCS using fixed depth bulk density calculations at the baseline measurement and then at project end can lead to significant errors owing the compaction / de-compaction of the soil [2], [21], [30] To minimise this source of error, and align with the FAO recommendations [20] the ESM approach may be adopted to calculate the change in SCS during the lifetime of a project.

In order to implement the ESM method the dry soil mass and cross-sectional area of the sample core relating to a series of contiguous soil segments is required. To minimise the interpolation errors at least 3 segments should be collected that span the depth profile for which the soil carbon stock is to be estimated, and a cubic spline interpolation undertaken [31]. However, for soil depths less than 60cm a 2-segment estimation may be used.

As ESM uses soil mass per unit area as the index, there is no necessity to calculate the soil bulk density within each increment, an "apparent soil bulk density" may be used (based on the nominal volume of the soil increment of $Volume_{sample} = \pi \times \left(\frac{d}{2}\right)^2 \times depth\ increment$)[1] *in lieu* of the true field SBD. This approach means that several SBD errors:

- Compaction of soil cores during sampling [23], [32].
- Soil bulk density changes during the lifetime of the project [2].

have negligible effects on an ESM calculation [33] and the removal of the effect of such sampling errors can improve the ability to observe small changes in soil properties [21], [34]

7. Calculation of Soil Organic Carbon Stock

7.1. Soil Organic Carbon Stock estimation based on Fixed Depth assessment

The simplest assessment of soil organic carbon stock (SCS) arises from the summation of the soil carbon stock at each sampling point for each depth increment and can be represented as:

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[1] Where composite samples are taken the sample volume is multiplied by the number of samples in the composite to provide the total sample volume.

$$SCS_a = \sum_i SOC_i \times h_i \times \rho_i \times (1 - RF) \qquad \text{(Eq. 4)}$$

Where:

SCS_a	is the calculated soil carbon sock per area *a,* the sum of the calculated soil carbon stock as each depth increment,
SOC_i	is the measured SOC concentration (%) in depth increment *i* at a specific sample location,
h_i	is the length of depth increment *i,*
ρ_i	is the fine soil SBD for the depth increment *i* at a specific sample location,
RF	is the volumetric coarse rock (>2mm) fragment.

The total SCS_{total} for the project is then:

$$SCS_{total} = \sum SCS_a \qquad \text{(Eq. 5)}$$

For a single time point this does provides a good assessment of the SCS.

7.2. Soil Carbon Stock estimation using Equivalent Soil Mass

7.2.1. ESM Calculation Principles – Soil Carbon Stock

For a given soil segment, of depth z (cm), the apparent soil bulk density, $\rho_{b,soil,z}$ (g cm^{-3}) can be calculated as:

$$\rho_{b,soil,z} = \frac{4 \times M_{sample,z}}{\pi \times d^2 \times z \times n} \qquad \text{(Eq. 6)}$$

Where:

$M_{sample,z}$	(g) is the mass of the oven dried fine soil (<2mm) sample collected for depth z,
d	is the diameter of the soil core (cm),
z	is the depth of the soil core segment (cm),
n	is the number of cores within the composite sample (if applicable)

and for any soil segment the mass of soil, $M_{soil,z}$, is simply:

$$M_{soil,z} = \rho_{b,soil,z} \times z \qquad \text{(Eq. 7)}$$

Combining and simplifying Eq.s 6 & 7 gives:

$$M_{soil,z} = 100 \times \frac{4 \times Mass_{sample,z}}{\pi \times d^2 \times n} \qquad \text{(Eq. 8)}$$

Where:

100	is the multiplication factor to convert from g cm^{-2} to t ha^{-1}.

The SCS$_z$ for the depth increment, z, is then simply:

$$SCS_z = M_{soil,z} \times SOC_z \qquad \text{(Eq. 9)}$$

Where:

SOC_z	is the measured SOC concentration (%) in depth increment z.

7.2.2. ESM Calculation Principles – Mineral Soil Mass

$M_{soil,z}$ represents the total soil mass per hectare, for depth z, however the ESM calculations require a constant reference between sampling points and thus needs to only account for what accumulates and stabilizes the SOC [35] Thus only the mineral part of the soil (<2mm, fine earth) , $M_{mineral,z}$, should be uses as the measure of soil mass .

$$M_{mineral,z} = M_{soil,z} - \left(\frac{M_{soil,z} \times SOC_z}{0.58}\right) \qquad \text{(Eq. 10)}$$

Where:

SOC_z	is the measured SOC concentration (%) in depth increment z,
0.58	is an acceptable conversion factor for SOC to SOM based on the “van Bemmelen factor” [36].[2]

7.2.3. ESM Calculation

To facilitate the ESM interpolation the cumulative mass of both mineral soil mass, M_i , and SCS, SCS_i , are required:

$$M_i = \sum_{z=1}^{i} M_{mineral,z} \qquad SCS_i = \sum_{z=1}^{i} SCS_z \qquad \text{(Eq.s 11a \& b)}$$

Where the collected soil profile has 3 or more points the interpolation should use a cubic spline fit [31], and the calculation of the carbon stock at a chosen reference soil mass may follow the R-code script described in “SimpleESM: R script to calculate soil organic carbon and nitrogen stocks at Equivalent Soil Mass”, [37] to provide the ESM2 “alternative” ESM values. Alternative calculations scripts are acceptable provided they adopt a cubic spline fit to the soil profile data.

8. Project Documentation

Both the baseline SCS assessment and the final SCS assessment should be reported in a document and GIS dataset/s that contains, as a minimum, the following information:

- Site and sampling details,
- Sampling design, strategy and stratification,
- Number and locations of samples,
- Sample collection, handling and laboratory testing methodologies,
- Results of laboratory testing analysis
- Calculation of SCS across the project area. For the final (or interim reports) the changes in SCS from baseline values should also be calculated.

The report should identify each parcel, sub-area and provide results and statistical analysis for each.

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[2] This factor is based on the assumption that soil organic matter comprised 58% w/w carbon, first suggested by Emil Wolff in 1864, [38] and then by J van Bemmelen in 1890. [36] For the purposed used here it is deemed an acceptable conversion factor to provide an adequate assessment of mass of soil associated with soil organic matter. Pribyl [39] has shown that 1.724 should not be considered a universally applicable factor to convert between SOM and SOC.

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10. APPROVALS

Version:				
3.0	Name	Position	Signature	Date
Created By:	D Gollins	Scientific Director, Verdant Carbon Ltd		March 25
Reviewed By:	Scientific Board			March 25
Approved By:	Douglas Wanstall	UKCCC Commissioner		March 25

11. CHANGE HISTORY

Date	Version	Created by	Description of Change(s)
	3.0	D. Gollins	Replaces legacy UKCCC document titled: Soil testing protocol