Verified Carbon Standard

VCS Methodology

VM0042

METHODOLOGY FOR IMPROVED AGRICULTURAL LAND MANAGEMENT

Version 2.0

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Sectoral Scope 14

Version 1.0 of this methodology was developed by TerraCarbon LLC and Indigo Ag. The lead authors were David Shoch and Erin Swails from TerraCarbon. Contributions from Indigo were made by (in alphabetical order): Chris Black, Charlie Brummit, Nell Campbell, Max DuBuisson, Dan Harburg, Lauren Matosziuk, Melissa Motew, Guy Pinjuv and Ed Smith. Version 1.0 was approved on 19 October 2020.

Version 2.0 of this methodology was prepared by Verra. Revisions to the uncertainty section were prepared by Dan Kane and Jaclyn Kachelmeyer, TerraCarbon LLC with input from Brian McConkey, Viresco Solutions and Beth Ziniti, Applied Geosolutions; and in consultation with several external experts.

CONTENTS

1 SOURCES

This methodology is based on the following methodologies:

- *VM0017 Adoption of Sustainable Agricultural Land Management, v1.0*
- *VM0022 Quantifying N2O Emissions Reductions in Agricultural Crops through Nitrogen Fertilizer Rate Reduction, v1.1*
- *VM0026 Methodology for Sustainable Grassland Management, v1.1*

This methodology uses the latest versions of the following Clean Development Mechanism (CDM) tools:

- *Estimation of Carbon Stocks and Change in Carbon Stocks of Trees and Shrubs in A/R CDM Project Activities*
- *Simplified Baseline and Monitoring Methodology for Small Scale CDM Afforestation and Reforestation Project Activities Implemented on Lands Other Than Wetlands*
- *Tool for Testing Significance of GHG Emissions in A/R CDM Project Activities*
- *Methodological Tool: Common Practice*
- *Tool for the Identification of Degraded or Degrading Lands for Consideration in Implementing CDM A/R Project Activities*
- *Tool: Project and Leakage Emissions from Biomass*

2 SUMMARY DESCRIPTION OF THE METHODOLOGY

Table 1: Additionality and crediting baseline methods

Additionality and Crediting Method	
Additionality	Project Method
Crediting Baseline	Project Method

This agricultural land management (ALM) methodology provides procedures to estimate the greenhouse gas (GHG) emission reductions and removals (CO_2, CH_4 and N_2O) resulting from the adoption of improved ALM practices. The methodology is compatible with regenerative agriculture and has a particular focus on increasing soil organic carbon (SOC) storage.

The crediting baseline and additionality are determined via a project method (Table 1). The baseline scenario assumes the continuation of pre-project ALM practices. Practices in the baseline scenario are determined by applying a minimum three-year historical look-back period to produce an annual schedule of activities (i.e., tillage, planting, harvest and fertilization events) for each sample unit within the project area (e.g., for each field), to be repeated over the baseline period.[1] Baseline emissions/stock changes are then modeled. Alternatively, baseline SOC stock change may be directly measured in “baseline control sites” managed according to pre-project practices as set out in the schedule of activities. The baseline scenario is re-evaluated as required by the latest version of the *VCS Standard*, and revised, where necessary, to reflect current agricultural production in the region.

Additionality is demonstrated by a barrier analysis and showing that the practice change implemented under the project activity is not common practice. A practice change constitutes any of the following:

- Adoption of a new practice (e.g., adoption of one or more of the practices covered in the categories included in Applicability Condition 1);
- Cessation of a pre-existing practice (e.g., stop tillage or irrigation);
- Adjustment to a pre-existing practice; or
- Some combination of the above.

Any quantitative adjustment (e.g., decrease in fertilizer application rate) must exceed five percent of the pre-existing value to qualify as a practice change.

The methodology provides three approaches to quantifying emission reductions and removals resulting from the adoption of improved ALM practices.

Quantification Approach 1: Measure and Model – a biogeochemical, process-based model is used to estimate GHG fluxes related to SOC stock changes, soil methanogenesis and use of nitrogen fertilizers and nitrogen-fixing species. Edaphic characteristics and actual agricultural practices implemented, measured initial SOC stocks and climatic conditions in sample fields are used as model inputs. Periodic measurements of SOC stocks are required every five years at minimum (see Table 8).

Quantification Approach 2: Measure and Re-Measure – direct measurement is used to quantify changes in SOC stocks. This approach is relevant where models are unavailable or have not yet been validated or parameterized for a particular region, crop or practice, or where project proponents prefer to use a direct measurement approach for SOC stock change. Quantification Approach 2 directly measures SOC stock changes in the baseline scenario in linked baseline control sites.

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[1] ALM projects are required to periodically reassess their baseline. See the latest version of the *VCS Standard* for further details on baseline re-assessment requirements.

Quantification Approach 3: Default Factors – CO_2 flux from fossil fuel combustion and N_2O and CH_4 fluxes, excluding CH_4 flux from methanogenesis, are calculated using default emission factors.

The quantification approach varies by emission/removal type. Approaches to quantification of contributing sources of CO_2, CH_4 and N_2O emissions are listed in Table 5.

3 DEFINITIONS

In addition to the definitions set out in the VCS document *Program Definitions*, the following definitions apply to this methodology.

Annual
A plant species that within one year completes its life cycle, reproduces and dies.

Baseline control site
Defined area that is managed according to pre-project (baseline) practices (as set out in the schedule of activities) for direct measurement of baseline soil organic carbon stock change. It is linked to and representative of the land in one or more sample units. Baseline control sites may be within or outside of the project area.

Historical look-back period
The time period prior to the project start date covering at minimum three years and one complete crop rotation. The historical look-back period is used to produce the schedule of activities (see definition below).

Improved agricultural land management practice
An agricultural practice yielding increased soil organic carbon storage or other climate benefit, involving a refinement to fertilizer or other soil amendment application, water management/irrigation, tillage, residue management, crop planting and harvesting and/or grazing practices.

Inelastic neutron scattering (INS)
An in-field (in situ) measurement technique based on the detection and analysis of gamma rays emitted by soil elements after irradiation with neutrons. It is also known as neutron-stimulated gamma ray analysis or spectroscopy.

Infrared spectroscopy
Mid-infrared (MIR), near-infrared (NIR) and visible near-infrared (Vis-NIR) spectroscopy, including diffuse reflectance spectroscopy (DRS) and diffuse reflectance infrared Fourier transform spectroscopy (DRIFT). Vis-NIR combines the visible and near-infrared electromagnetic range and usually refers to a wavelength range from 350 to 2500 nm (visible range is between

350 and 700 nm). MIR covers the range between 4000 cm^{-1} and 600 (or 400) cm^{-1}, depending on the instrument.

Laser-induced breakdown spectroscopy (LIBS)
Application of a high-energy pulse to soil samples to generate a high-temperature plasma, which emits radiation at different wavelengths depending on the elements present in the sample

Nitrogen-fixing species
Any plant species that associates with nitrogen-fixing microbes found within nodules formed on the roots, including but not limited to soybeans, alfalfa and peas

Organic nitrogen fertilizer
Any organic material containing nitrogen, including but not limited to animal manure, compost and biosolids

Perennial
A plant species whose life cycle, reproduction and death extends across multiple years

Professional agronomist
An individual with specialized knowledge, skills, education, experience or training in crop and/or soil science. Such individuals may be agricultural experts like soil scientists, husbandry specialists, agronomists or representatives of a governmental agricultural body.

Project domain
Set of conditions (including crop type, soil texture and climate) in which model application has been validated (see *VMD0053 Model Calibration and Validation Guidance for the Methodology for Improved Agricultural Land Management*)

Sample point
Sample location of undefined area

Sample unit
Defined area within the project for which emissions reductions and removals are estimated using the selected quantification approach. The entire project area is divided into multiple sample units that must be demonstrated to be homogenous for the purposes of estimating emission reductions and removals (ERRs) (i.e., similar management activities, soil type, climate etc.). Estimates of ERRs for each sample unit within the project area are then aggregated to produce an estimate for the entire project area. Sample units must be clearly defined in the description of the sampling design provided in the project description document.

Schedule of activities
Annual schedule of historical management/activity practices applied in the baseline scenario over the historical look-back period (e.g., tillage, planting, harvest and fertilization events). These practices are determined following the data requirements given in Box 1.

Synthetic nitrogen fertilizer
Any fertilizer made by chemical synthesis (solid, liquid, gaseous) and containing nitrogen. This may be a single nutrient fertilizer product (only including N), or any other synthetic fertilizer containing N, such as multi-nutrient fertilizers (e.g., N–P–K fertilizers) and "enhanced-efficiency" N fertilizers (e.g., slow release, controlled release and stabilized N fertilizers).

Woody perennials
Trees and shrubs having a life cycle lasting more than two years, excluding cultivated annual species with lignified tissues, such as cotton or hemp

4 APPLICABILITY CONDITIONS

This methodology applies to a broad range of project activities that increase SOC storage and/or decrease net emissions of CO_2, CH_4 and N_2O from ALM operations compared to the baseline scenario. The methodology is globally applicable.

This methodology is applicable under the following conditions:

1) Projects must introduce or implement one or more new changes to pre-existing ALM practices which:
    a) Improve fertilizer (organic or inorganic) management;
    b) Improve water management/irrigation;
    c) Reduce tillage/improve residue management;
    d) Improve crop planting and harvesting (e.g., improved agroforestry, crop rotations, cover crops); and/or
    e) Improve grazing practices.

    Appendix 1 provides a non-exhaustive list of eligible ALM practices. A change in practice constitutes adoption of a new practice, cessation of a pre-existing practice or adjustment to a pre-existing practice that results in GHG emissions reduction or removal.

2) Projects that introduce or implement quantitative adjustments (e.g., decrease in fertilizer application rate) must exceed five percent of the pre-existing value, calculated as the average value over the historical look-back period, developed for the baseline schedule of activities (see Section 6). Appendix 1 gives additional details and guidance on practices and on determining practice change.
3) Project activities must be implemented on land that is either cropland or grassland at the project start date. The land must remain cropland or grassland throughout the project crediting period except under the following scenarios:

    a) Introduction of temporary grassland into cropland where it is demonstrated, prior to the project start date and to the addition of new project activity instances, that the integration of forage crops (e.g., annual/perennial grasses, legumes) into annual crops is part of a planned, long-term ALM system (e.g., integrated crop-livestock system). Project proponents must provide documentation of the long-term management plans, covering the duration of the project, that describe proposed practices, crops and expected benefits and outcomes of integrated grassland-cropland management; or
    b) A one-time conversion from grassland to cropland or vice versa where it is demonstrated, prior to project validation, that project lands in the baseline scenario are degraded and the introduction of improved land use change practices would significantly improve soil health. Project proponents must provide documentation demonstrating that lands are degraded at the start of the project and degradation will continue in the baseline scenario due to the presence of degradation drivers or pressures in the baseline scenario. See Appendix 2 for procedures on how to propose this type of land use change.
4) Empirical or process-based models used to estimate stock change/emissions via Quantification Approach 1 must be:
    a) Publicly available, though not necessarily free of charge, from a reputable and recognized source (e.g., the model developer's website, IPCC or government agency). Sufficient conceptual documentation of inputs, outputs and information on how the model functionally represents SOC dynamics must be accessible to the public. Providing the source code or an API for independent replication of calculations is not required;
    b) Shown in peer-reviewed scientific studies to successfully simulate changes in SOC and trace gas emissions resulting from the changes in ALM practices included in the project description;
    c) Able to support repetition of the project model simulations. This includes clear versioning of the model used in the project and stable software support, as well as fully reported sources and values for all parameters used with the project version of the model. Where multiple sets of parameter values are used in the project, clearly identify the sources of varying parameter sets and how they were applied to estimate stock change/emissions in the project. Acceptable sources include peer-reviewed literature and statements from appropriate expert groups that demonstrate evidence of expertise with the model via authorship of peer-reviewed model publications or authorship of reports for entities supporting climate-smart agriculture. These sources must describe the datasets and statistical processes used to set parameter values;
    d) Validated per datasets and procedures detailed in Section 5.2 of *VMD0053 Model Calibration and Validation Guidance for the Methodology for Improved Agricultural Land Management.* Model prediction error must be calculated using datasets as described in Section 5.2.5 of VMD0053 and must use the same

parameters or sets of parameters applied to estimate stock change/emissions in the project; and

e) Using the same model version in the baseline and project scenarios. Further, the same parameters/parameter sets must be used in the baseline and project scenarios. Model input data must be derived following guidance in Table 6 and Table 8. Model uncertainty must be quantified following guidance in Section 8.6. Models may be recalibrated or revised based on new data, or a new model may be applied, provided the above requirements are met.

This methodology is not applicable under the following conditions:

5) The project area has been cleared of native ecosystems within the 10-year period immediately prior to the project start date.

6) The project activity is expected to cause a sustained reduction in productivity of greater than 5 percent, as demonstrated by peer-reviewed and/or published studies on the activity in the region or a comparable region.

7) The project activity is biochar application. Biochar may be applied as a soil amendment in the project area provided that the total organic carbon content[2] of the biochar applied is subtracted from the estimated SOC stock change in the project scenario at each verification event.

8) The project activities occur on a wetland; this condition does not exclude crops subject to artificial flooding where it is demonstrated that crop cultivation does not impact the hydrology of any nearby wetlands.

5 PROJECT BOUNDARY

The spatial extent of the project boundary is all lands planning to implement the proposed improved ALM practice(s). Carbon pools included in the project boundary in the baseline and project scenarios are listed in Table 2.

Table 2: Selected carbon pools in the baseline and project scenarios

Source	Included?	Justification/Explanation
Aboveground woody biomass	Yes / Optional	Aboveground woody biomass must be included where project activities significantly reduce the pool compared to the baseline. In all other cases, aboveground woody biomass is an optional pool.

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[2] To estimate the total carbon content of the applied biochar, project proponents should follow the procedures set out in Sections 8.2.2.1 or 8.2.2.2 (for high- or low-technology production facilities, respectively) in the latest version of *VM0044 Methodology for Biochar Utilization in Soil and Non-Soil Applications*. Where the technology production facility type is not known, procedures in the low-technology approach (Section 8.2.2.2) should be followed for conservativeness.

Aboveground non-woody biomass	No	Carbon pool is not included because it is not subject to significant changes or potential changes are transient in nature
Belowground woody biomass	Optional	Belowground woody biomass may optionally be included where project activities significantly increase the pool compared to the baseline
Belowground non-woody biomass	No	Carbon pool is not included because it is not subject to significant changes or potential changes are transient in nature
Dead wood	No	Carbon pool is not included because it is not subject to significant changes or potential changes are transient in nature
Litter	No	Carbon pool is not included, because it is not subject to significant changes or potential changes are transient in nature
SOC	Yes	Major carbon pool affected by project activity that is expected to increase in the project scenario
Wood products	No	Carbon pool is optional for ALM project methodologies and may be excluded from the project boundary

GHG sources included in the project boundary in the baseline and project scenarios are listed in Table 3. Specific carbon pools and GHG sources may be deemed de minimis and need not be accounted for (i.e., value set to zero) where together the omitted decrease in carbon stocks (in carbon pools) or increase in GHG emissions (from GHG sources) amounts to less than five percent of the total GHG benefit generated by the project. This includes sources and pools that cause project and leakage emissions. This and all subsequent references to de minimis demonstration are conducted via application of the CDM *Tool for testing significance of GHG emissions in A/R CDM project activities.*[3] The SOC pool must be included in the project boundary (i.e., it must be monitored as part of a VM0042 project and is not allowed to be deemed de minimis).

Table 3: GHG sources included in or excluded from the project boundary in the baseline and project scenarios

Source	Gas	Included?	Justification/Explanation
SOC	CO_2	Yes	Quantified as stock change in the pool, rather than an emissions source (see Table 2)
Fossil fuel	CO_2	S*	Sources of fossil fuel emissions are vehicles (mobile sources, such as trucks, tractors) and mechanical equipment required by the ALM activity.
Liming	CO_2	S*	Application of limestone or dolomite as soil amelioration may represent a significant source of CO_2.

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[3] Since project activities are not permitted to result in a sustained reduction in productivity (including animal weight gains) or sustained displacement of any pre-existing productive activity, feedlots are conservatively excluded from the project boundary.

Soil methanogenesis	CH_4	S*	Anoxic conditions in soils may lead to soil methanogenesis.
Enteric fermentation	CH_4	Yes	Where livestock are present in the project or baseline scenarios, CH_4 emissions from enteric fermentation must be included in the project boundary.
Manure deposition	CH_4	Yes	Where livestock are present in the project or baseline scenarios, CH_4 and N_2O emissions from manure deposition and management must be included in the project boundary.
	N_2O	Yes	
Use of nitrogen fertilizers	N_2O	Yes	Where, in the baseline scenario, the project area would have been subject to nitrogen fertilization or where nitrogen fertilization is greater in the with-project scenario relative to the baseline scenario, N_2O emissions from nitrogen fertilizers must be included in the project boundary.
Use of nitrogen-fixing species	N_2O	Yes	Where nitrogen-fixing species are planted in the project, N_2O emissions from nitrogen-fixing species must be included in the project boundary.
Biomass burning	CO_2	Excluded	Carbon stock decreases due to burning are accounted as a carbon stock change.
Biomass burning	CH_4	S*	Biomass burning releases CH_4.
	N_2O	S*	Biomass burning releases N_2O.
Woody biomass	CO_2	S*	Quantified as stock change in the pool rather than an emissions source (see Table 2)

S* – Must be included where the project activity significantly increases emissions (i.e., by more than five percent) compared to the baseline scenario and may be included where the project activity reduces emissions compared to the baseline scenario.

6 BASELINE SCENARIO

Continuation of pre-project ALM practices is the most plausible baseline scenario. For each sample unit (e.g., for each field), baseline scenario practices are set to match the practices implemented in the historical look-back period, creating an annual schedule of activities to be repeated throughout the first baseline period.[4] Baseline emissions/stock changes are then modeled (Quantification Approach 1) or (for SOC stock change only) directly measured in baseline control sites subject to the annual schedule of activities (Quantification Approach 2). Note that under Quantification Approach 1, direct SOC stock estimates are also required at *t* = 0 to serve as model input for model initialization.[5] The crops and practices assumed in the baseline scenario must be re-assessed in accordance with the requirements of the latest

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[4] For example, where the schedule of activities includes tillage events in years *t* = −3 and −1 but does not involve tillage in year *t* = −2, the schedule of activities for tillage in the baseline scenario would be tillage, no tillage, tillage. This pattern would be repeated as follows for the first baseline period: tillage, no tillage, tillage, tillage, no tillage, tillage, tillage, no tillage, tillage, tillage.

[5] Per Table 6, baseline SOC stocks may be (back-)modeled to *t* = 0 from measurements collected within ±5 years of *t* = 0.

version of the *VCS Standard* and revised, where necessary, to reflect current agricultural production in the region.[6]

Development of Schedule of Activities in the Baseline Scenario

For each sample unit, a schedule of activities in the baseline scenario will be determined by assessment of practices implemented during the period prior to the project start date. The interval over which practices are assessed, x years, must be a minimum of three years and must include at least one complete crop rotation, where applicable. Where a crop rotation is not implemented in the baseline, $x = 3$ years. For each year, $t = -1$ to $t = -x$, information on ALM practices must be determined, per the requirements presented in Table 4.

Table 4: Minimum specifications for ALM practices in the baseline scenario

ALM Practice	Qualitative	Quantitative
Crop Planting and Harvesting	• Crop type(s)	• Approximate date(s) planted (where applicable) • Approximate date(s) harvested/terminated (where applicable) • Crop yield (where applicable)
Nitrogen Fertilizer Application	• Manure (Y/N) • Compost (Y/N) • Synthetic N fertilizer (Y/N)	• Manure type application rate (where applicable) • Compost type application rate (where applicable) • N application rate in synthetic fertilizer (where applicable)
Tillage and/or Residue Management	• Tillage (Y/N) • Crop residue removal (Y/N)	• Depth of tillage (where applicable) • Frequency of tillage (where applicable) • Percent of soil area disturbed (where applicable) • Percent of crop residue removed (where applicable)
Water Management/Irrigation	• Irrigation (Y/N) • Flooding (Y/N)	• Irrigation rate (where applicable)
Grazing Practices	• Grazing (Y/N) • Animal type (where applicable) • Harvesting/mowing (Y/N)	• Animal stocking rate (i.e., number of animals and length of time grazing in each area annually, where applicable) • Frequency of harvest

In most cases, quantitative information is associated with related qualitative information (see Box 1). Thus, a negative response on a qualitative element would mean there is no quantitative information related to that practice, whereas a positive response on a qualitative element will require quantitative information related to that practice.

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[6] See Section 3.2.7 of the *VCS Standard*, *v4.4* (or equivalent in latest version)

The schedule of activities, beginning with year $t = -x$, will be applied in the baseline scenario, from $t = 1$ onward, repeating every x years through the end of the first baseline period.

The schedule of activities in the baseline scenario will be valid until re-assessment is required as per the latest version of the *VCS Standard*. At the end of each baseline period, production of the commercial crop(s) in the baseline scenario will be re-evaluated. Published regional (sub-national) agricultural production data from within the five years immediately preceding the end of the current baseline period must be consulted.

- Where there is evidence of continued production of the relevant commercial crop(s) using the same ALM practices in the region, the baseline scenario will be valid as-is, continuing with the previous schedule of activities.
- Where there is no evidence of continued production of the relevant commercial crop(s), a new schedule of ALM activities (evaluated against common practices in the region) will be developed based on written recommendations for the sample field provided by independent professional agronomists, agricultural experts such as soil scientists, husbandry specialists and agronomists, or representatives of a governmental agricultural body, including government agricultural extension agents. Recommendations must provide sufficient detail to produce the minimum specifications on ALM practices for the baseline scenario as outlined in Table 4.
- Where more than one value is documented in recommendations (e.g., where a range of application rates are prescribed in written recommendations), the principle of conservatism must be applied, selecting the value that results in the lowest expected emissions (or highest rate of stock change) in the baseline scenario.
- Where the evidence is not field-specific, conservatively derived field-specific values must be supported by a documented method justifying the appropriateness of selection.

7 ADDITIONALITY

This methodology uses a project method for the demonstration of additionality. Project proponents using this methodology must:

1) Demonstrate regulatory surplus;
2) Identify institutional barriers that would prevent the implementation of a change in pre-existing ALM practices; and
3) Demonstrate that the adoption of the suite of proposed project activities is not common practice.

Further details on each of these steps are provided below.

Step 1: Regulatory surplus

The project proponent must demonstrate regulatory surplus in accordance with the rules and requirements set out in the latest version of the *VCS Standard*.

Step 2: Identify institutional barriers that would prevent implementation of a change in pre-existing ALM practices

The project proponent must determine whether there are cultural and/or social barriers (e.g., cultural practices and social norms, attitudes and beliefs) to the proposed change(s) in ALM expected that prevent implementation of the change without the intervention of the project proponent and the resulting revenue from the sale of VCUs. The project proponent must list and describe barriers to the implementation of proposed changes to pre-project ALM practices to establish that the change would not occur if the project was not undertaken by the project proponent and registered as a VCS project.

Demonstration of cultural and/or social barriers must be supported by peer-reviewed and/or published studies specific to the project region. Where evidence is not available for the project region, evidence from other regions may be used where justification is given demonstrating how those cultural and/or social barriers are also applicable to the project region.

Such barriers may include traditional knowledge or lack thereof, laws and customs, market conditions and lack of motivating incentives to change practices, including, but not limited to:

- Traditional equipment and technology;
- Grower risk tolerance and beliefs about the feasibility of adopting new practices, and implications of their decisions;
- Grower openness to new ideas and perceptions of the magnitude of the change; and
- Barriers associated with grower identity.

Step 3: Demonstrate that adoption of the suite of proposed project activities is not common practice

The project proponent must determine whether the proposed project activity or suite of activities[7] are common practice in each region included within the project spatial boundary. Common practice is defined as greater than 20 percent adoption.[8] To demonstrate that a project activity or suite of activities is not common practice, the project proponent must show that the weighted mean adoption rate of the two (or more) predominant[9] proposed project

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[7] The suite of activities refers to all activities implemented across the aggregated project. It does not refer to the activities implemented on each individual farm.

[8] Twenty percent is the precedent for a common practice threshold established in Section 18 of the CDM *Methodological tool: Common practice*. Available at: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-24-v1.pdf.

[9] Determined based on the extent of the project area (i.e., hectares) covered.

activities within the project spatial boundary is below 20 percent[10] (see Equation (1)). Therefore, in projects where the adoption rate of one activity (e.g., reduced tillage) is greater than 20 percent, the project must include a proportionally higher ratio of other activities with lower adoption rates (e.g., cover crops, improved fertilizer management) to bring the weighted average of proposed project activities below 20 percent. An individual activity with an existing adoption rate in the relevant region below or equal to 20 percent is always considered additional. An individual activity with an existing adoption rate greater than 20 percent may only be considered additional through the assessment of the weighted mean adoption rate for all project lands within that region.

Categories of project activities for the demonstration of common practice may be defined according to the categories in the evidence provided, or using the categories outlined in Appendix 1.

Evidence must be provided in the form of publicly available information contained in:

a) Agricultural census or other government (e.g., survey) data;

b) Peer-reviewed scientific literature;

c) Independent research data; or

d) Reports or assessments compiled by industry associations.

To demonstrate common practice, the project area must be stratified to the state or provincial level (or equivalent second-order jurisdiction) in the countries where the project is being developed. Where supporting evidence is unavailable at the state/provincial level (e.g., in developing countries), aggregated data or evidence at a national or regional level may be used with justification. Where stratification based on geopolitical boundaries is impractical (e.g., due to lack of data), other forms of stratification, such as major soil types or cropping zones, may be used with justification. The same stratification approach and data sources must be applied across the entire project to maintain the integrity of the common practice demonstration. Where a data source is unavailable for a subset of the project region, justification must be provided for use of a different data source.

Where evidence for a single proposed project activity in the region is not available from any of these sources, the project proponent may obtain a signed and dated attestation statement from a qualified independent local expert (e.g., agricultural extension agent, accredited agronomist) estimating the adoption rate for the weighted mean calculation. Where evidence on the suite of proposed activities is unavailable, a qualified independent local expert may provide a signed and dated attestation statement stating whether the proposed suite of project activities is common practice in the region.

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[10] Where a project is planning to implement two activities, common practice must be assessed based on the weighted mean of those two activities. Where only one activity is implemented, common practice must be assessed solely based on that activity's adoption rate (i.e., the adoption rate of that activity must be below 20 percent).

To calculate the weighted mean adoption rate in each region covered by the project area, Equation (1) must be applied.

$$AR = ((EA_{a1} \times PA_{a1}) + (EA_{a2} \times PA_{a2}) + \cdots + (EA_{ay} \times PA_{ay}) \tag{1}$$

Where:[11]

$$PA_{a1} = \frac{Area_{a1}}{(Area_{a1} + Area_{a2} + \cdots + Area_{ay})}$$

$$PA_{a2} = \frac{Area_{a2}}{(Area_{a1} + Area_{a2} + \cdots + Area_{ay})}$$

$$PA_{ay} = \frac{Area_{ay}}{(Area_{a1} + Area_{a2} + \cdots + Area_{ay})}$$

And:

AR = Weighted average adoption rate in the region (%)
EA_{ay} = Existing adoption rate of proposed project activity *ay* in the region (%)
PA_{ay} = Ratio of proposed project-level adoption of activity *ay* relative to proposed project-level adoption of all activities in the region
$Area_{ay}$ = Area of proposed project-level adoption of activity *ay* in the region (hectares)
ay = 1, …, *ay* proposed project activities ranked by area covered in the region, where 1 = largest area covered

A project proponent may include areas where more than one project activity will be implemented on the same land (e.g., reduced tillage plus cover crops). Evidence of existing adoption rates for the combined (two or more) activities should be used to calculate the weighted mean adoption rate of the proposed combined activities. Where evidence on existing adoption rates for the combined activities is not available, the project proponent may multiply the existing adoption rates (i.e., pre-project) of the individual activities to estimate the combined activity adoption rate.[12] For example, with a statewide existing adoption rate of 40 percent for reduced tillage and 10 percent for cover-cropping, the adoption rate to be applied in Equation (1) for lands combining (stacking) these two activities would be 4 percent (i.e., 0.4 × 0.1 = 0.04).

Where Steps 1–3 are satisfied, the proposed project activity is additional.

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[11] Note that parameters are described below equations only at their first appearance.

[12] In practice, this encourages “stacking” of new activities to enhance GHG reductions and/or removals compared to implementing only one new activity on a given area or farm.

For registered grouped projects with an initial set of project activity instances, Appendix 3 provides a recommended process for assessing whether new project activity instances are common practice.

8 QUANTIFICATION OF GHG EMISSION REDUCTIONS AND REMOVALS

8.1 Summary

This methodology provides a flexible approach to quantifying emission reductions and removals from the adoption of improved ALM practices in the project compared to the baseline scenario. Baseline and project emissions are defined in terms of flux of CH_4, N_2O and CO_2 in tonnes of CO_2e per unit area[13] per monitoring period. Within each sample unit, stock and emission changes in each included pool or flux are treated on a per unit area basis in accounting procedures. Section 8.5 provides equations using total stock or emission changes in the project to quantify net GHG reductions and removals. Where a monitoring period spans multiple calendar years, the equations quantify emission reductions by year to appropriately define vintage periods.

The approaches for quantifying CO_2, CH_4 and N_2O emissions are listed in

Table 5. Where more than one quantification approach is allowable for a given gas and source, more than one approach may be used provided that the same approach is used for a given sample unit in both the project and baseline scenarios.

Table 5: Summary of allowable quantification approaches

GHG/ Pool	Source	Quantification Approach 1: Measure and Model*	Quantification Approach 2: Measure and Remeasure	Quantification Approach 3: Default Factors
CO_2	SOC	X	X	
	Fossil fuel			X
	Liming			X
	Woody biomass**			
CH_4	Soil methanogenesis	X		
	Enteric fermentation			X
	Manure deposition			X
	Biomass burning			X
	Use of nitrogen fertilizers	X		X

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[13] Note that for reporting purposes hectares should be used as the unit area throughout this methodology.

N_2O	Use of nitrogen-fixing species	X		X
	Manure deposition			X
	Biomass burning			X

* Approach 1 may only be used where a valid model is available (see model requirements in VMD0053).
** Where included in the project boundary, woody biomass is calculated using the CDM A/R tools *Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities* and *Simplified baseline and monitoring methodology for small scale CDM afforestation and reforestation project activities implemented on lands other than wetlands*. Where woody biomass is harvested, projects must calculate the long-term average GHG benefit following guidance in the latest version of the *VCS Methodology Requirements*, Section 3.6 and the latest version of the *VCS Standard*, Section 3.2.

For each pool/source, subdivisions of the project area using different quantification approaches must be stratified and accounted separately. A project may switch between allowable quantification approaches for a given source during the project crediting period, provided that the same approach is used for both the project and baseline scenarios. The quantification approaches are as follows.

Quantification Approach 1: Measure and Model

An acceptable model is used to estimate GHG flux based on soil characteristics, implemented ALM practices, measured initial SOC stocks and climatic conditions in sample units. Measurements of SOC stocks are required every five years or more frequently (see Table 8). The remeasurement data is used to re-estimate model prediction error and recalibrate the model (i.e., “true-up”, see Section 8.6.1.3).

Quantification Approach 2: Measure and Remeasure

Direct measurement is used to quantify changes in SOC stocks. This approach is relevant where models are unavailable or have not yet been validated or parameterized, or where project proponents prefer to use a direct measurement approach for SOC stock change. The baseline scenario is measured and remeasured directly at a baseline control site linked to one or more sample units. Quantification Approach 2 is only applicable to SOC.

Quantification Approach 3: Default Factors

GHG flux is calculated following the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* using equations contained in this methodology.

Where a given activity is not practiced in the baseline or project scenarios, resulting in an effective input of zero for any equation element in this methodology, that equation element is not required.

8.2 Baseline Emissions

Quantification Approach 1

The baseline is modeled for each sample unit. The model serves to project future stock change/emissions resulting from the schedule of ALM activities taking place in the baseline scenario (derived in Section 6). Further guidance on biophysical model inputs is elaborated in

Table 6.

Table 6: Guidance on collection of biophysical model inputs for the baseline scenario, where required by the model selected

Model Input Category	Timing	Approach
SOC content and bulk density to calculate SOC stocks (initial)	Determined prior to project intervention via direct measurements at *t* = 0 or (back-) modeled to *t* = 0 from measurements collected within ±5 years of *t* = 0	Directly measured via conventional analytical laboratory methods, for example dry combustion, or proximal sensing techniques (e.g., INS, LIBS, MIR and Vis-NIR) with known uncertainty following the criteria in Appendix 4 at *t* = 0 or (back-) modeled to *t* = 0 following VMD0053 guidance. See parameter table for $\overline{SOC_{bsl,i,t}}$.
Soil properties (other than bulk density and SOC)	Determined prior to project intervention	Directly measured or determined from published soil maps with known uncertainty. Estimates from direct measurements must: • Be derived from representative (unbiased) sampling; and • Ensure accuracy of measurements through adherence to best practices.
Climate variables (e.g., precipitation, temperature)	Continuously monitored ex post	Measured for each model-specific meteorological input variable at its required temporal frequency (e.g., daily) for the model prediction interval. Measurements are taken at the closest continuously monitored weather station not exceeding 50 km from the sample field, or from a synthetic weather station (e.g., PRISM[14]).

Quantification Approach 2

Baseline SOC stocks are measured and remeasured directly at baseline control sites which are linked to sample units. Control sites are managed by applying schedules of activities established in the baseline scenario for the corresponding sample unit (derived in Section 6). Control sites must comply with the similarity criteria listed in Table 7 and be within 250 km of their linked sample units. It is possible for one control site to be linked to more than one sample unit provided the control site meets the similarity criteria for each sample unit to which it is linked.

Control sites may be managed by project proponents, implementing partners or by entities external to the project (e.g., experimental research stations outside of the project area). Control sites must be sufficiently large to ensure that any changes in SOC stocks are driven by baseline management practices (i.e., edge effects must be eliminated) and to allow for baseline

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[14] Available at: https://climatedataguide.ucar.edu/climate-data/prism-high-resolution-spatial-climate-data-united-states-maxmin-temp-dewpoint

practices to continue unimpeded (e.g., tractors, combines or other equipment must be able to operate as they would under normal conditions). Where adverse conditions such as extreme weather events or pest outbreaks arise during the project crediting period, managers of control sites may deviate from the schedule of activities to mitigate negative impacts as they would in the absence of a carbon project (e.g., halt irrigation if there is excess rainfall).

Under this approach at least three control sites are required across the entire project area, but more will decrease uncertainty, particularly where the total number of control sites is less than ten. Note that with increasing variability and heterogeneity of the project area, a higher number of control sites will be necessary to ensure that similarity criteria are met. Since stratified random sampling is the required sampling strategy for this methodology (see Section 8.2.1), there must be at least one control site per stratum. Baseline SOC stocks must be reported for the baseline control sites and for each stratum within the project area. See Section 8.6.2 as well as the *Soil Organic Carbon MRV Sourcebook for Agricultural Landscapes*[15] for further information on the number of samples to collect.

Table 7: Similarity criteria for linking baseline control sites to sample units under Quantification Approach 2

Control Site Similarity Criterion	Threshold*
Topography	Most frequent slope class[16] must be the same in the sample units and control sites (to be determined from a slope map or via a GIS slope analysis[17]). For control sites classified as hilly, steep or very steep, the aspect must be within 30° of the cardinal direction of the linked sample unit.
Soil texture to depth of project boundary (minimum 30 cm)	Average soil texture must be in the same FAO[18] soil textural class as the average soil texture of the linked sample unit. Note that where significant textural differences are evident within 0–30 cm depth, texture should be determined separately for the different soil horizons within that depth range.
Soil group	Soil group must be within the same reference soil group, according to the FAO *World Reference Base for Soil Resources,*[19] as the linked sample unit.
Average SOC percent by dry weight to depth of project boundary (minimum 30 cm)	The percentage must not be significantly different from the mean percentage SOC of the linked sample unit at a 90 percent confidence level.

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[15] Box 3.5. Available at: https://openknowledge.worldbank.org/handle/10986/35923

[16] See Table 10 in Appendix 5 for soil slope classifications

[17] See Appendix 5 for workflow steps to determine the most frequent slope class using geographical information systems (GIS)

[18] See Annex 4 in the FAO *World Reference Base for Soil Resources 2014* available at: https://www.fao.org/3/i3794en/I3794en.pdf. The USDA Soil Texture Calculator https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167 may be used to determine the soil texture class based on percent sand and clay content.

[19] See Table 2 of the FAO *World Reference Base for Soil Resources 2014*

Control Site Similarity Criterion	Threshold*
Historical ALM activities	Historical ALM activities must be the same as in the linked sample unit for at least five years prior to project start date: • Tillage – no tillage, conservation tillage or conventional (full) tillage • Residue management – retained or burnt/removed • Cropping – continuous cash crops, cover crops or fallows • Organic amendments (manure or compost) – yes or no • Irrigation – yes or no Note that not all of these activities will be universally relevant to all agricultural systems and the project proponent must therefore provide evidence supporting the selected historical ALM activities used to link control sites with sample units. See Box 1 for guidance on data sources for establishing historical ALM activities.
Historical land cover**	For lands converted up to 50 years prior to the project start date, the site must be converted from the same major land cover type (e.g., forestland, grassland, savanna) as the linked sample unit within ±10 years.
Native vegetation	The site must be within the same terrestrial ecoregion[20] as the linked sample unit.
Climate zone	The site must be within the same IPCC-defined climate zone as the linked sample unit.
Precipitation***	The site must have mean annual precipitation within ±100 mm of the linked sample unit.

*Estimates of these quantitative thresholds must be derived from unbiased, representative sampling of the control site. Accuracy must be ensured through adherence to best practices (to be determined by the project proponent and outlined in the monitoring plan – see Section 9.3).

**Estimated based on historical satellite or aerial imagery or, where imagery is unavailable, confirmed via local expert attestation

***Estimated based on measurements taken at the closest continuously monitored weather station not exceeding 50 km from the control site or from a synthetic weather station (e.g., PRISM)

Quantification Approach 3

The baseline is calculated for each sample field using the equations provided. Emissions resulting from the schedule of ALM activities taking place in the baseline scenario (derived in Section 6) are estimated using default emission factors and data are determined for each sample field at validation.

Figure 1 summarizes which equations are to be applied to each GHG flux depending on the selected quantification approach (see also Table 5).

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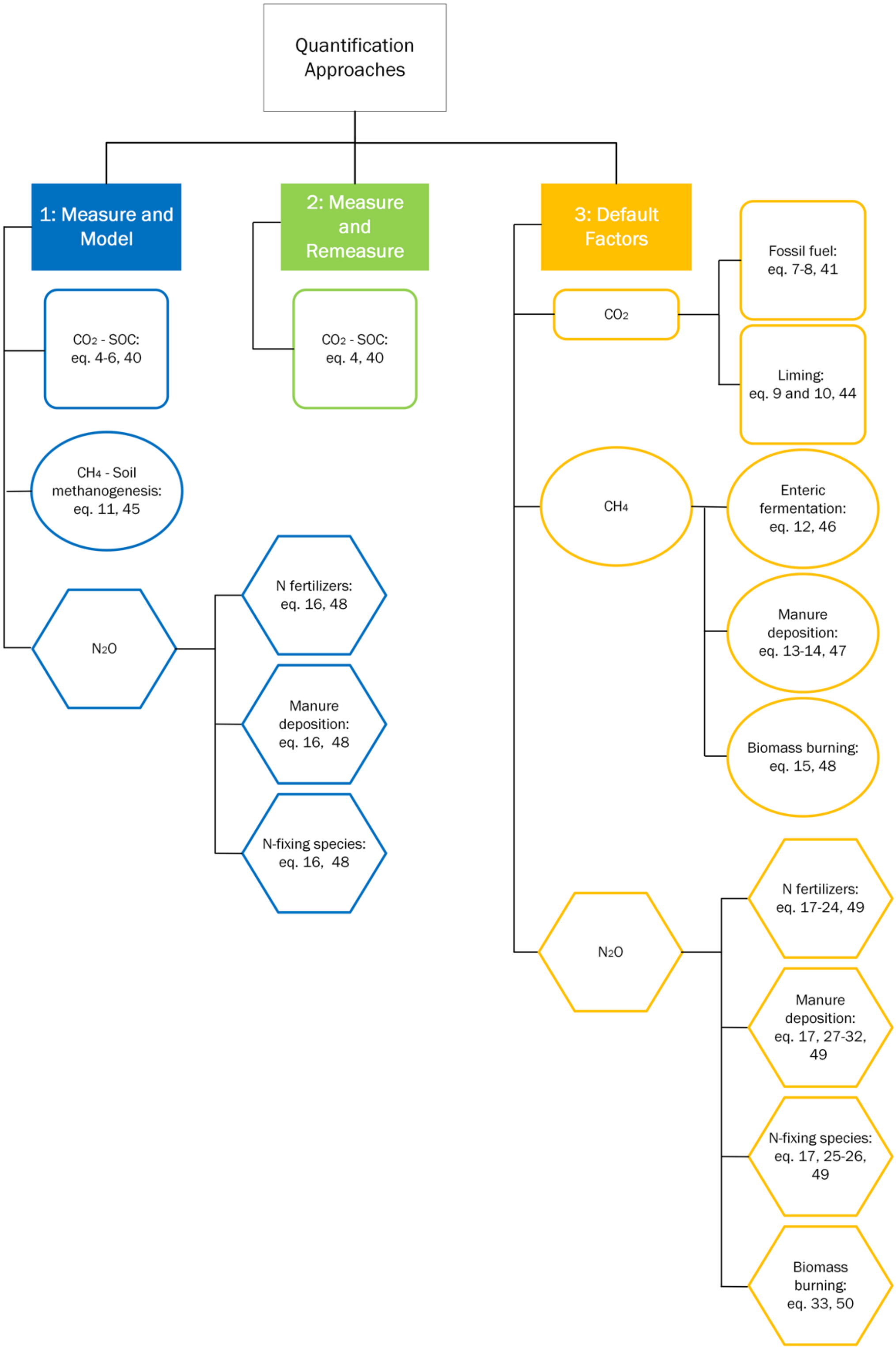
[20] As defined in the WWF Terrestrial Ecoregions of the World database. Available at: https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world

Figure 1: Equation map of this methodology



Woody biomass must be quantified as per

Table 5 using the CDM A/R tools *Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities* and *Simplified baseline and monitoring methodology for small scale CDM afforestation and reforestation project activities implemented on lands other than wetlands*, and reported using Equations (42) and (43). Where woody biomass is harvested, projects must calculate the long-term average GHG benefit following guidance in the latest version of the *VCS Methodology Requirements*, Section 3.6 and the latest version of the *VCS Standard*, Section 3.2.

8.2.1 Soil Organic Carbon Stocks

Direct measurements of SOC stocks are required under Quantification Approach 1 as model inputs for baseline setting and at a minimum every five years after for model true-up. Direct measurements of SOC stocks are also required under Quantification Approach 2 to determine the baseline and project SOC stocks at the project start date and at each verification event. Note that the initially measured SOC stocks (at t = 0 determined through direct measurements or (back-) modeled to t = 0 from measurements collected within ±5 years of t = 0) are the same in both the baseline and project scenarios at the outset of the project (i.e., $SOC_{wp,i,0} = SOC_{bsl,i,0}$) when following Quantification Approach 1.

Soil sampling and modeling should occur on a point or small plot (i.e., composite sample) basis to allow for accurate estimation of sampling error and its contribution to the uncertainty of credit estimates. Points should be allocated within the lowest level sample units using an acceptable approach. If small plots or composite samples are used, the distance between points in such a sample should be minimized to reduce the possibility that spatial variability is poorly estimated.

SOC stock estimates generated must:

1) Be demonstrated to be unbiased and derived from representative sampling; and
2) Ensure the accuracy of measurements and procedures through the employment of quality assurance/quality control (QA/QC) procedures (to be determined by the project proponent and outlined in the monitoring plan).

Measurement procedures for SOC and bulk density must be thoroughly described, including all sample handling, analysis preparation and analysis techniques. Further details on each of these procedures are provided in the following sections.

8.2.1.1 General Requirements for Soil Sampling

Standard QA/QC procedures for soil inventory including field data collection and data management must be applied.

Use or adaptation of QA/QC procedures available from published handbooks is recommended, such as those produced by FAO and available on the FAO Soils Portal, the ISO standards on soil sampling (including *ISO 18400-104 Soil quality — Sampling — Part 104: Strategies*) or the IPCC *Good Practice Guidance LULUCF 2003*.

For all directly sampled parameters, the project monitoring plan must clearly spatially delineate the sample population and specify sampling intensities, selection of sample units and sampling stages (where applicable). The statistical analysis measurements plan must be submitted as part of the sampling plan for project validation. The detailed sample design must be specified in the monitoring plan, and unbiased estimators of population parameters identified for application in calculations.

- For re-sampling purposes, it is essential to georeference sample locations[21] and consider seasonal variability.
- Sampling and re-sampling campaigns must be conducted during the same season over time.
- Where organic amendments are applied, projects should delay sampling or re-sampling to the latest time possible after the previous application and the shortest time possible before the next application.

8.2.1.2 Sampling Design: Stratified Random Sampling

Soil sampling must be conducted following the stratified random sampling strategy.[22] Each sampling unit within the project area should be divided into homogenous strata based on factors influencing SOC stock distribution (see below). Random samples should be taken in each stratum.

Project-specific strata, their area and the sampling points within strata must be reported in a spreadsheet and submitted as an annex to project documentation at every verification.

The stratified random sampling strategy may be nested within a multi-stage sampling approach, but in such cases stratified random sampling must be employed in the stage directly before the sample point stage (see Appendix 6 for an example). An alternative sampling strategy may be proposed for a project via a methodology deviation that provides sufficient scientific rationale and project-specific justification.[23]

Random sampling schemes, without prior stratification, frequently produce relatively high uncertainties when estimating SOC stock changes. Grid or linear sampling patterns require a large number of samples and may produce biased results due to linear features across the site

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[21] Depending on the available GPS precision, these locations may be delineated as areas of several meters in diameter.

[22] Detailed descriptions of how to conduct stratified random sampling are provided in Annex 3 in FAO (2020) and in Module B in World Bank (2021).

[23] See Section 3.19 of the latest version of the *VCS Standard* for detailed guidance.

being under- or over-represented. Therefore, grid or linear sampling patterns are not recommended.

- To determine strata, the best available data on factors expected to affect the response of SOC stocks to the project activities must be used.
- Projects must report the factors used in stratification and how strata were developed.

Numerous factors determine SOC heterogeneity at field (10–100 ha) and landscape (100–1000 ha) scales, including climate, topography, historical land use and vegetation, parent material, soil texture and soil type. Stratifying the project area (or sampling units) into homogenous strata defined by factors that influence SOC stocks (e.g., those listed as similarity criteria for defining baseline control sites in Table 7) should improve sampling efficiency and reduce errors associated with project-scale estimates of SOC stocks.

The sampling design must capture variability within the project area. An unbiased spatially stratified approach is important to capture variations in SOC across the project area. The larger a stratum's area and the greater the expected or known variability within a stratum, the higher the number of samples that must be taken within the stratum. The soil maps and databases of the FAO SOILS PORTAL[24] (e.g., the Harmonized World Soil Database), SoilGrids[25] or locally available (digital) soil maps may help in choosing different strata. In addition, soil texture is easily estimated in the field. Since land use and management history frequently align with existing fields, field boundaries should be taken into account when delineating strata, though potential changes in field boundaries over time must be considered. Defined strata should remain stable over time.

The number of homogeneous sites (i.e., the number of strata) and soil composite samples should be maximized. The number of years required to detect SOC stock changes decreases with increasing sample number. Compositing or bulking soil samples may better represent spatial variability, but may reduce ability to detect SOC stock changes over time. Therefore at least 3–5 composite samples should be taken within each stratum for model true-up or when using Quantification Approach 2.

8.2.1.3 Collection of Soil Samples

The following are guidelines for collection of soil samples and reporting.

1) Soil sampling must follow established best practices, such as those found in FAO (2019, 2020), De Gruijter et al. (2006), Smith et al. (2020) and Soil Science Division Staff (2017).

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[24] Available at: http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/

[25] Available at: https://soilgrids.org/

2) Where possible, SOC content and soil mass should be obtained from the same sample, or alternatively from adjacent samples taken during the same sampling event. Where multiple cores are composited to create a single sample, these cores must be from the same depth and fully homogenized prior to subsampling.
3) All organic material (e.g., living plants, crop residue) must be cleared from the soil surface before soil sampling.
4) Soil mass must not include particles greater than 2 mm in diameter (i.e., gravel/stones) nor plant material.[26]
5) Soil samples must be shipped within five days of collection and kept refrigerated until shipping if they are stored in sealed plastic bags. Alternatively, soil samples should be aerated during storage, avoiding mixing of the different soil materials. Drying and sieving procedures must follow laboratory-specific SOPs and be consistent for all samples collected as part of the project.
6) Reporting of SOC stock changes from direct measurements under Quantification Approaches 1 and 2 must occur on an equivalent soil mass (ESM) basis.
    a) The mass of soil in each depth layer depends on the bulk density of the respective layer. Therefore, it is important to differentiate between soil mass layers and soil depth layers to enable a consistent comparison of SOC changes and differences between two points in time and between baseline and project areas.
    b) SOC stocks and stock changes must be reported to a minimum depth of 30 cm. To eliminate the need for extrapolation outside of the measured range, soils must be sampled deeper than the minimum 30 cm required for reporting SOC stock changes.
    c) To enable the ESM approach, soil samples at re-sampling must be taken as contiguous cores divided into at least two increments.
    d) The project proponent may select the depth increments sampled according to expected loosening or compaction effects throughout the project lifetime, because bulk density changes as a result of improved ALM will depend largely on land use in the project area and the ALM practices implemented as part of the project.
    e) Where possible, soils should be sampled to 50 cm depth (i.e., in two depth increments 0–30 cm and 30–50 cm), following the recommendation in Wendt and Hauser (2013) to ensure sub-soil depth layers are sufficient to permit adjustments. From these measurements, the ESM layers and the depths to

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[26] Beem-Miller et al. (2016) provide a useful approach to ensuring high-quality sampling in rocky agricultural soils.

reference mass (see columns K and L in Figure 2) will be determined (see Section 8.2.1.6). Note that only the soil mass is required from the two separate depth increments. SOC content analysis may be performed on only one sample after mixing the two depth increments.

7) Soils less than 30 cm deep (e.g., due to shallow bedrock or a formed hardpan) must be sampled to the depth of the impeding layer. Sample units with these characteristics must be documented and SOC stocks must only be reported to the sampled depth.[27]

8) Geographic locations of intended sampling points must be established prior to sampling. The location of both the intended sampling point and the actual sampling point must be recorded.

9) The number of samples to be taken within each stratum should be determined based on the expected variance, to reduce overall uncertainty. A pre-sampling of 5 to 10 soil samples per stratum may provide an estimate of SOC variance where up-to-date soil data are unavailable.

10) A power analysis may be conducted to calculate the number of samples needed to enable accounting of a minimum detectable difference, following Equations (2) and (3) (FAO, 2019). However, projects are not required to take this number of samples.

$$MDD \geq \frac{S}{\sqrt{n}} \times \left(t_{\alpha,\upsilon} + t_{\beta,\upsilon}\right) \tag{2}$$

$$n \geq \left(\frac{S \times (t_{\alpha} + t_{\beta})}{MDD}\right)^2 \tag{3}$$

Where:

MDD = Minimum detectable difference
S = Standard deviation of the difference in SOC stocks between t_0 and t_1
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 percent)
t_β = One-sided quartile of the t-distribution corresponding to a probability of type II error β (e.g., 90 percent)

Further guidance on stratification and sampling strategies over large scales is found in Aynekulu et al. (2011), FAO (2019), de Gruijter et al. (2016), Hengl et al. (2003), ISO (2018, p. 18), Maillard et al. (2017), Mudge et al. (2020) and Vanguelova et al. (2016).

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[27] This will affect the ESM layers of the respective sampling points shallower than 30 cm (see Section 8.2.1.6).

8.2.1.4 Measurements of SOC Content

SOC content with known uncertainty should be measured using dry combustion (Dumas method). In addition, the following proximal sensing techniques are allowed: infrared spectroscopy, including near infrared (NIR), visible near infrared (Vis-NIR) and mid-infrared spectroscopy (MIR); laser-induced breakdown spectroscopy (LIBS); and inelastic neutron scattering (INS, also known as neutron-stimulated gamma ray analysis or spectroscopy). Appendix 4 provides criteria for evaluating the use of IR spectroscopy, LIBS and INS.

Walkley-Black (wet) oxidation and loss on ignition (LOI) are not recommended due to accuracy concerns but may be applied where no other method is available. The use of remote sensing to estimate and monitor SOC stock changes is not currently allowed. However, it may be permitted in the future once a specific VCS tool is developed and available that provides guidelines that ensure the robustness and reliability of this method.

8.2.1.5 Measurements of Bulk Density

Bulk density must be measured in the field following the core, excavation or clod methods. Best practice guidance and established standards for these methods, such as *ISO 11272:2017 Soil quality — Determination of dry bulk density*, must be used. Bulk density as soil mass per volume of sampling cores must not include particles greater than 2 mm in diameter (i.e., gravel/stones/rocks/coarse fraction) nor plant material. The coarse fraction may be estimated by sieving and weighing stones/rocks/gravel and multiplying them by the average density of the coarse material.[28]. Beem-Miller et al. (2016) provide a useful approach to ensuring high-quality sampling in rocky agricultural soils. Samples for bulk density, dry soil mass and SOC content should be taken at the same time and from sampling locations within a few meters of the previous sampling point location, avoiding edge effects and disturbed areas.

8.2.1.6 Calculation of SOC Stocks

To ensure that changes in SOC stocks do not arise solely from a temporal change in bulk density (related to ALM practices), SOC stock changes based on measurements (including for baseline and true-up measurements under Quantification Approach 1) must be calculated on an ESM basis[29] following the procedures explained in Ellert and Bettany (1995), Wendt and Hauser (2013) or von Haden et al. (2020). The SOC mass of each depth layer or increment per unit area is calculated as the product of soil mass and organic carbon (OC) concentration, where soil mass is obtained by dividing the dry sample mass in each depth layer by the area sampled by the probe or auger (Wendt & Hauser, 2013):

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[28] FAO (2019) provides details on a method to estimate the coarse mineral fraction volume. Although this is a precise method, it is not required under this methodology as it is very time-consuming.

[29] Note that calibration and validation datasets used for modeling under Quantification Approach 1 do not need to meet the ESM requirement.

$$M_{n,dl,SOC} = \left(\frac{M_{n,dl,sample}}{\pi \left(\frac{D}{2}\right)^2 \times N} \times 10\ 000 \right) \times OC_{n,dl} \qquad (4)$$

Where:

$M_{n,dl,SOC}$ = SOC mass in soil sample *n* in depth layer *dl* (kg/ha)
$M_{n,dl,sample}$ = Soil mass of sample *n* in depth layer *dl* (g)
D = Inside diameter of probe or auger (mm)
N = Number of cores sampled (unitless)
$OC_{n,dl}$ = Organic carbon content in sample *n* in depth layer *dl* (g/kg)
10 000 = Conversion factor from g/mm^2 to kg/ha

The cumulative SOC mass per unit area is then calculated by summing all sampled depth increments (see column H in Figure 2). The spreadsheet[30] provided in Wendt and Hauser (2013) may be used by project proponents to calculate reference equivalent soil masses and adjustments independently from sampled depth increments by using a cubic spline function (see Figure 2). Alternatively, the R script[31] provided in von Haden et al. (2020) may be applied. Where one of these templates is used, a copy showing the calculation procedures must be submitted as part of the documentation to be validated by the VVB.

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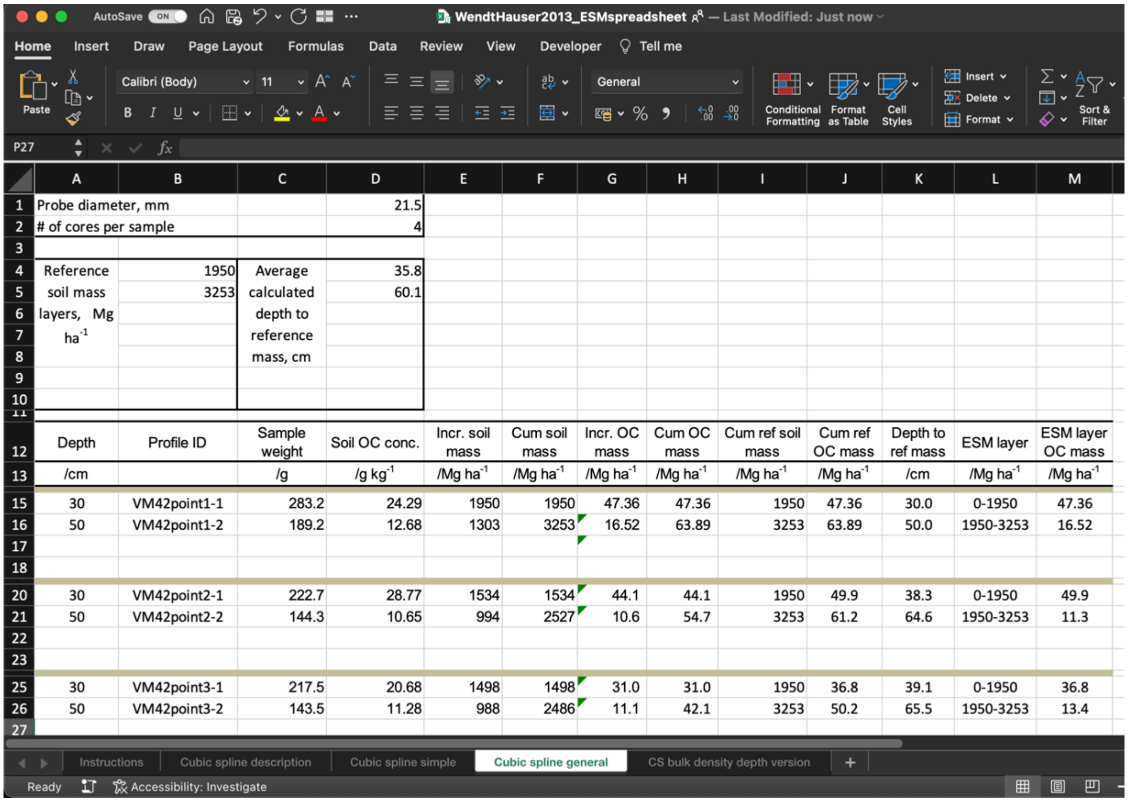
[30] Available at: https://docs.google.com/open?id=0BzxNFfzLbFxjSG9RWlpwQ0FXc0k

[31] Available at: https://onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2Fgcb.15124&file=gcb15124-sup-0002-Supinfo.pdf



Probe diameter, mm			21.5
# of cores per sample			4
Reference soil mass layers, Mg ha^{-1}	1950 3253	Average calculated depth to reference mass, cm	35.8 60.1

Depth	Profile ID	Sample weight	Soil OC conc.	Incr. soil mass	Cum soil mass	Incr. OC mass	Cum OC mass	Cum ref soil mass	Cum ref OC mass	Depth to ref mass	ESM layer	ESM layer OC mass
/cm		/g	/g kg^{-1}	/Mg ha^{-1}	/Mg ha^{-1}	/Mg ha^{-1}	/Mg ha^{-1}	/Mg ha^{-1}	/Mg ha^{-1}	/cm	/Mg ha^{-1}	/Mg ha^{-1}
30	VM42point1-1	283.2	24.29	1950	1950	47.36	47.36	1950	47.36	30.0	0-1950	47.36
50	VM42point1-2	189.2	12.68	1303	3253	16.52	63.89	3253	63.89	50.0	1950-3253	16.52
30	VM42point2-1	222.7	28.77	1534	1534	44.1	44.1	1950	49.9	38.3	0-1950	49.9
50	VM42point2-2	144.3	10.65	994	2527	10.6	54.7	3253	61.2	64.6	1950-3253	11.3
30	VM42point3-1	217.5	20.68	1498	1498	31.0	31.0	1950	36.8	39.1	0-1950	36.8
50	VM42point3-2	143.5	11.28	988	2486	11.1	42.1	3253	50.2	65.5	1950-3253	13.4

Figure 2: Screenshot of ESM spreadsheet provided in Wendt and Hauser (2013)

In the example in **Figure 2**, the cumulative OC mass to 30 cm depth at the first sampling point *VM42point1-1* is 47.36 Mg/ha (t/ha; cell H15) for a cumulative soil mass of 1950 Mg/ha (cell F15). Column I provides standard cumulative reference masses, which in this example have been adjusted to cover the maximum measured soil mass (sample with highest density). The respective ESM layers are set as 0–1950 Mg/ha and 1950–3253 Mg/ha (column L). The values in column M represent the OC mass in each ESM layer, calculated with a cubic spline function. To be compliant with reporting SOC stocks to at least 30 cm depth on an ESM basis, projects must use the cumulative reference soil mass for 0–1950 Mg/ha. In this example, the three sample points would have SOC mass of 47.36 Mg/ha (cell J15), 49.9 Mg/ha (cell J20) and 36.8 Mg/ha (cell J25). These match the values in column M. These values must then be used to calculate an average SOC mass valid for the total area of the sample unit. When re-sampling and comparing SOC stocks at two different points in time, the same principle must be applied to ensure that results are reported for an ESM that covers the measured sample with the highest density (i.e., highest determined soil mass).

Note that under Quantification Approach 1, SOC stocks for model initialization may be calculated using Equation (5) where models use SOC stocks as an input rather than ingesting SOC content and bulk density values separately. Where models require bulk density inputs, such bulk density measurements must be taken following the approach described in Section 8.2.1.5.

$$SOC_{model} = 0.1 \times BD_{corr} \times d \times OC_{n,dl} \tag{5}$$

Where:

SOC_{model}	=	SOC stock as model input data (t/ha)
BD_{corr}	=	Corrected bulk density of the fine soil fraction, after subtracting the mass proportion of the coarse fragments (g/cm^3)
d	=	Soil depth (cm)
0.1	=	Conversion factor from g/cm^2 to t/ha

Finally, modeled SOC stocks under Quantification Approach 1 must be calculated using Equation (6) and following the guidance in VMD0053:

$$SOC_{bsl,i,t} = ƒ(SOC_{bsl,i,t}) \tag{6}$$

Where:

$SOC_{bsl,i,t}$	=	Estimated carbon stocks in the SOC pool in the baseline scenario for sample unit *i* at the end of year *t* (t CO$_2$e/ha)
$ƒ(SOC_{bsl,i,t})$	=	Modeled SOC stocks in the baseline scenario for sample unit *i* in year *t*, calculated by modeling SOC stock changes over the course of the preceding year (t CO$_2$e/ha)
i	=	Sample unit

8.2.2 Change in Carbon Stocks in Aboveground and Belowground Woody Biomass

Where carbon stocks in aboveground and belowground woody biomass are included in the project boundary per Table 3, the change in carbon stocks in trees ($\Delta C_{TREE,bsl,i,t}$) and shrubs ($\Delta C_{SHRUB,bsl,i,t}$) in the baseline for sample unit *i* in year *t* are calculated using the CDM A/R tools *Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities* and *Simplified baseline and monitoring methodology for small scale CDM afforestation and reforestation project activities implemented on lands other than wetlands.*

Where woody biomass is included in the project boundary, the relevant Afforestation, Reforestation and Revegetation (ARR) requirements in the latest version of the *VCS Methodology Requirements* apply. Where woody biomass is harvested, projects must calculate the long-term average GHG benefit following guidance in the latest version of the *VCS Methodology Requirements* Section 3.6, and the latest version of the *VCS Standard* Section 3.2.

8.2.3 Carbon Dioxide Emissions from Fossil Fuel Combustion

Where carbon dioxide emissions from fossil fuel are included in the project boundary per Table 3, they are quantified in the baseline scenario under Quantification Approach 3, using Equations (7) and (8).

Parameter $\overline{CO_2\_ff_{bsl,i,t}}$ is estimated using the following equation:

$$\overline{CO_2\_ff_{bsl,i,t}} = (\sum_{j=1}^{J} EFF_{bsl,j,i,t})/A_i \tag{7}$$

Where:

$\overline{CO_2\_ff_{bsl,i,t}}$ = Areal mean carbon dioxide emissions from fossil fuel combustion in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$EFF_{bsl,j,i,t}$ = Carbon dioxide emissions from fossil fuel combustion in the baseline scenario in vehicle/equipment type *j* for sample unit *i* in year *t* (t CO_2e)

A_i = Area of sample unit *i* (ha)

j = Type of fossil fuel (gasoline or diesel)

The parameter $EFF_{bsl,j,i,t}$ is estimated using the following equation:

$$EFF_{bsl,j,i,t} = FFC_{bsl,j,i,t} \times EF_{CO2,j} \tag{8}$$

Where:

$FFC_{bsl,j,i,t}$ = Consumption of fossil fuel type *j* for sample unit *i* in year *t* (liters)

$EF_{CO2,j}$ = Emission factor for combustion of fossil fuel type *j* (t CO_2e/liter)

8.2.4 Carbon Dioxide Emissions from Liming

Application of calcitic limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) releases bicarbonate ($2HCO_3^-$), which evolves into CO_2 and water (H_2O) as carbonate limes dissolve. Where one of the ALM practices is liming and resulting carbon dioxide emissions are not deemed de minimis, they are quantified in the baseline scenario under Quantification Approach 3 using Equations (9) and (10).

Parameter $\overline{CO2\_lime_{bsl,i,t}}$ is estimated using the following equation:

$$\overline{CO2\_lime_{bsl,i,t}} = EL_{bsl,i,t} / A_i \tag{9}$$

Where:

$\overline{CO2\_lime_{bsl,i,t}}$ = Areal mean carbon dioxide emissions from liming in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$EL_{bsl,i,t}$ = Carbon dioxide emissions from liming in the baseline scenario for sample unit *i* in year *t* (t CO_2e)

$$EL_{bsl,i,t} = ((M_{Limestone,bsl,i} \times EF_{Limestone}) + (M_{Dolomite,,bsl,i} \times EF_{Dolomite})) \times \frac{44}{12} \tag{10}$$

Where:

$M_{Limestone,bsl,i}$ = Amount of calcitic limestone ($CaCO_3$) applied to sample unit *i* in year *t* (tonnes)

$EF_{Limestone}$ = Emission factor for calcitic limestone (0.12) (t C per t of limestone)

$M_{Dolomite,bsl,i}$ = Amount of dolomite ($CaMg(CO_3)_2$) applied to sample unit *i* in year *t* (tonnes)

$EF_{Dolomite}$ = Emission factor for dolomite (0.13) (t C per t of dolomite)

44/12 = Molar mass ratio of CO_2 to C applied to convert CO_2-C emissions to CO_2 emissions

8.2.5 Methane Emissions from the SOC Pool

Where methane emissions from soil methanogenesis are included in the project boundary per Table 3, they are quantified in the baseline scenario under Quantification Approach 1 using Equation (11).

$$\overline{CH4\_soil_{bsl,i,t}} = GWP_{\mathrm{CH4}} \times ƒ(CH4\_soil_{bsl,i,t}) \tag{11}$$

Where:

$\overline{CH4\_soil_{bsl,i,t}}$ = Areal mean methane emissions from SOC pool in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$ƒ(CH4\_soil_{bsl,i,t})$ = Modeled methane emissions from the soil in the baseline scenario for sample unit *i* in year *t*, calculated by modeling soil methane fluxes over the course of the preceding year (t CO_2e/ha)

GWP_{CH4} = Global warming potential for CH_4 (t CO_2e/t CH_4)

8.2.6 Methane Emissions from Livestock Enteric Fermentation

Where methane emissions from livestock enteric fermentation are included per Table 3, they are quantified in the baseline scenario under Quantification Approach 3 using Equation (12). Following the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, quantification must be differentiated by livestock type, manure management system and productivity system.

$$\overline{CH4\_ent_{bsl,\iota,t}} = (\frac{GWP_{CH4} \times \sum_{l=1}^{L} Pop_{bsl,l,i,t,P} \times EF_{ent,l,P}}{1000})/A_i \tag{12}$$

Where:

$\overline{CH4\_ent_{bsl,\iota,t}}$ = Areal mean methane emissions from livestock enteric fermentation in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)
$Pop_{bsl,l,i,t,P}$ = Population of grazing livestock of type *l* in sample unit *i* for productivity system *P* in year *t* in the baseline scenario (head numbers)
$EF_{ent,l,P}$ = Enteric fermentation emission factor for livestock type *l* in productivity system *P* (kg CH_4/(head × year))
l = Type of livestock
P = Productivity system
1000 = Conversion factor from kg to t

8.2.7 Methane Emissions from Manure Deposition

Where methane emissions from manure deposition are included in the project boundary per Table 3, they are quantified in the baseline scenario under Quantification Approach 3 using Equations (13) and (14).

$$\overline{CH4\_md_{bsl,\iota,t}} = \frac{GWP_{CH4} \times \sum_{l=1}^{L}(Pop_{bsl,l,i,t,P} \times VS_{l,i,t,P} \times AWMS_{l,i,t,P,S} \times EF_{CH4,md,l,P,S})}{10^6 \times A_i} \tag{13}$$

Where:

$\overline{CH4\_md_{bsl,\iota,t}}$ = Baseline areal mean CH_4 emissions from manure deposition in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)
$VS_{l,i,t,P}$ = Average volatile solids excretion per head for livestock type *l* in sample unit *i* for productivity system *P* in year *t* (kg volatile solids/(head × day)
$AWMS_{l,i,t,P,S}$ = Fraction of total annual volatile solids for each livestock type *l* in sample unit *i*, that is managed in manure management system S in the project area, for productivity system *P* (dimensionless)
$EF_{CH4,md,l,P,S}$ = Emission factor for methane emissions from manure deposition for livestock type *l* for productivity system *P* in manure management system S (g CH_4/(kg volatile solids))
S = Manure management system
10^6 = Conversion factor from grams to tonnes

$$VS_{l,i,t,P} = \left(VS_{rate,l,P} \times \frac{W_{bsl,l,i,t,P}}{1000}\right) \times 365 \tag{14}$$

Where:

$VS_{rate,l,P}$ = Default volatile solids excretion rate for livestock type *l* for productivity system *P* (kg volatile solids/(1000 kg animal mass × day))

$W_{bsl,l,i,t,P}$ = Average weight in the baseline scenario of livestock type *l* for sample unit *i* in productivity system *P* in year *t* (kg animal mass/head)

1000 = Conversion factor kg per tonne

365 = Days per year

8.2.8 Methane Emissions from Biomass Burning

Where methane emissions from biomass burning are included in the project boundary per Table 3, they are quantified in the baseline scenario under Quantification Approach 3 using Equation (15).

$$\overline{CH4\_bb_{bsl,\iota,t}} = \left(\frac{GWP_{CH4} \times \sum_{c=1}^{C} MB_{bsl,c,i,t} \times CF_c \times EF_{c,CH4}}{10^6}\right)/A_i \qquad (15)$$

Where:

$\overline{CH4\_bb_{bsl,\iota,t}}$ = Methane emissions in the baseline scenario from biomass burning for sample unit *i* in year *t* (t CO_2e/ha)

$MB_{bsl,c,i,t}$ = Mass of agricultural residues of type *c* burned in the baseline scenario for sample unit *i* in year *t* (kg)

CF_c = Combustion factor for agricultural residue type *c* (proportion of pre-fire fuel biomass consumed)

$EF_{c,CH4}$ = Methane emission factor for the burning of agricultural residue type *c* (g CH_4/kg dry matter burnt)

c = Type of agricultural residue

10^6 = Conversion fractor from grams to tonnes

8.2.9 Nitrous Oxide Emissions from Nitrogen Fertilizers and Nitrogen-Fixing Species

Nitrous oxide emissions due to nitrification/denitrification include direct and indirect emissions from nitrogen fertilizers and direct emissions from nitrogen-fixing species. Where nitrous oxide emissions due to nitrogen inputs to soils from nitrogen fertilizers and nitrogen-fixing species are included in the project boundary per Table 3, they are quantified in the baseline scenario under Quantification Approaches 1 or 3. Under Quantification Approach 1, Equation (16) is used. Under Quantification Approach 3, Equations (17)–(26) are used. Following the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, quantification must be differentiated by livestock type, manure management system and productivity system.

Quantification Approach 1

Direct and indirect nitrous oxide emissions due to nitrogen inputs to soils (nitrogen fertilizers, manure deposition and nitrogen-fixing species) in the baseline scenario are quantified as:

$$\overline{N2O\_soil_{bsl,i,t}} = GWP_{N2O} \times f(N2O\_soil_{bsl,i,t}) \tag{16}$$

Where:

$\overline{N2O\_soil_{bsl,i,t}}$ = Areal mean direct and indirect nitrous oxide emissions due to nitrogen inputs to soils in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$f(N2O\_soil_{bsl,i,t})$ = Modeled nitrous oxide emissions from soil in the baseline scenario for sample unit *i* in year *t*, calculated by modeling soil fluxes of nitrogen forms over the course of the preceding year (t N_2O/ha)

GWP_{N2O} = Global warming potential for N_2O (t CO_2e / t N_2O)

Quantification Approach 3

Nitrous oxide emissions due to nitrogen inputs to soils in the baseline scenario are estimated by applying Equation (17).

$$N2O\_soil_{bsl,i,t} = N2O\_fert_{bsl,i.t} + N2O\_md_{bsl,i,t} + N2O\_Nfix_{bsl,i,t} \tag{17}$$

Where:

$N2O\_soil_{bsl,i,t}$ = Nitrous oxide emissions due to nitrogen inputs to soils in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$N2O\_fert_{bsl,i,t}$ = Nitrous oxide emissions due to fertilizer use in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$N2O\_md_{bsl,i,t}$ = Nitrous oxide emissions due to manure deposition in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$N2O\_Nfix_{bsl,i,t}$ = Nitrous oxide emissions from crop residues due to the use of N-fixing species in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

Where nitrous oxide emissions due to fertilizer use are included in the project boundary per Table 3, they are quantified in the baseline scenario using Equations (18)–(24).

$$N2O\_fert_{bsl,i,t} = N2O\_fert_{bsl,direct,i,t} + N2O\_fert_{bsl,indirect,i,t} \tag{18}$$

Where:

$N2O\_fert_{bsl,direct,i,t}$ = Direct nitrous oxide emissions due to fertilizer use in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$N2O\_fert_{bsl,indirect,i,t}$ = Indirect nitrous oxide emissions due to fertilizer use in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

Direct nitrous oxide emissions due to fertilizer use in the baseline scenario are quantified in Equations (19)–(21).

$$\overline{N2O\_fert_{bsl,direct,i,t}} = ((FSN_{bsl,i,t} + FON_{bsl,i,t}) \times EF_{Ndirect} \times 44/28 \times GWP_{N2O})/A_i \tag{19}$$

$$FSN_{bsl,i,t} = \sum_{SF} M_{bsl,SF,i,t} \times NC_{SF} \tag{20}$$

$$FON_{bsl,i,t} = \sum_{OF} M_{bsl,OF,i,t} \times NC_{OF} \tag{21}$$

Where:

$\overline{N2O\_fert_{bsl,direct,i,t}}$ = Areal mean direct nitrous oxide emissions due to fertilizer use in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$FSN_{bsl,i,t}$ = Synthetic N fertilizer applied to sample unit *i* in year *t* in the baseline scenario (t N)

$FON_{bsl,i,t}$ = Organic N fertilizer applied to sample unit *i* in year *t* in the baseline scenario (t N)

$EF_{Ndirect}$ = Emission factor for nitrous oxide emissions from N additions from synthetic fertilizers, organic amendments and crop residues (t N_2O-N/t N applied)

$M_{bsl,SF,i,t}$ = Mass of N-containing synthetic fertilizer type *SF* applied to sample unit *i* in year *t* in the baseline scenario (t fertilizer)

NC_{SF} = N content of synthetic fertilizer type *SF* (t N/t fertilizer)

$M_{bsl,OF,i,t}$ = Mass of N-containing organic fertilizer type *OF* applied to sample unit *i* in year *t* in the baseline scenario (t fertilizer)

NC_{OF} = N content of organic fertilizer type *OF* (t N/t fertilizer)

SF = Synthetic N fertilizer type

OF = Organic N fertilizer type

44/28 = Molar mass ratio of N_2O to N applied to convert N_2O-N emissions to N_2O emissions

Indirect nitrous oxide emissions due to fertilizer use in the baseline scenario are quantified in Equations (22)–(24).

$$\overline{N2O\_fert_{bsl,indirect,i,t}} = (N2O\_fert_{bsl,volat,i,t} + N2O\_fert_{bsl,leach,i,t})/A_i \tag{22}$$

$$N2O\_fert_{bsl,volat,i,t} = \begin{bmatrix} (FSN_{bsl,i,t} \times Frac_{GASF,l,S}) + \\ (FON_{bsl,i,t} \times Frac_{GASM,l,S}) \end{bmatrix} \times EF_{Nvolat} \times 44/28 \times GWP_{N2O} \tag{23}$$

$$N2O\_fert_{bsl,leach,i,t} = \begin{pmatrix} FSN_{bsl,i,t} + \\ FON_{bsl,i,t} \end{pmatrix} \times Frac_{LEACH,l,S} \times EF_{Nleach} \times \frac{44}{28} \times GWP_{N2O} \tag{24}$$

Where:

$\overline{N2O\_fert_{bsl,indirect,i,t}}$ = Areal mean indirect nitrous oxide emissions due to fertilizer use in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$N2O\_fert_{bsl,volat,i,t}$ = Indirect nitrous oxide emissions produced from atmospheric deposition of N volatilized due to fertilizer use in the baseline scenario in sample unit *i* in year *t* (t CO_2e)

$N2O\_fert_{bsl,leach,i,t}$ = Indirect nitrous oxide emissions produced from leaching and runoff of N, in regions where leaching and runoff occurs, due to fertilizer use in the baseline scenario in sample unit *i* in year *t* (t CO_2e)

$Frac_{GASF,l,S}$ = Fraction of all synthetic N added to soils that volatilizes as NH_3 and NO_x for manure management system *S* and livestock type *l* (dimensionless)

$Frac_{GASM,l,S}$ = Fraction of all organic N added to soils and N in manure and urine deposited on soils that volatilizes as NH_3 and NO_x for manure management system *S* and livestock type *l* (dimensionless)

EF_{Nvolat} = Emission factor for nitrous oxide emissions from atmospheric deposition of N on soils and water surfaces (t N_2O-N/(t NH_3-N + NO_x-N volatilized))

$Frac_{LEACH,l,S}$ = Fraction of N (synthetic or organic) added to soils and in manure and urine deposited on soils that is lost through leaching and runoff, in regions where leaching and runoff occurs, for manure management system *S* and livestock type *l* (dimensionless)

EF_{Nleach} = Emission factor for nitrous oxide emissions from leaching and runoff (t N_2O-N/t N leached and runoff)

Where nitrous oxide emissions due to the use of N-fixing species are included in the project boundary per Table 3, they are quantified in the baseline scenario using Equations (25) and (26).

$$\overline{N2O\_Nfix_{bsl,i,t}} = (F_{CR,bsl,i,t} \times EF_{Ndirect} \times \frac{44}{28} \times GWP_{N2O})/A_i \tag{25}$$

Where:

$\overline{N2O\_Nfix_{bsl,i,t}}$ = Areal mean nitrous oxide emissions from crop residues due to the use of N-fixing species in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$F_{CR,bsl,i,t}$ = Amount of N in N-fixing species (above- and belowground) returned to soils in the baseline scenario for sample unit *i* in year *t* (t N)

$$F_{CR,bsl,i,t} = \sum_{g=1}^{G} MB_{g,bsl,i,t} \times N_{content,g} \tag{26}$$

Where:

$MB_{g,bsl,i,t}$ = Annual dry matter (above- and belowground) of N-fixing species *g* returned to soils for sample unit *i* in year *t* (t dm)

$N_{content,g}$ = Fraction of N in dry matter for N-fixing species *g* (t N/t dm)

g = Type of N-fixing species

8.2.10 Nitrous Oxide Emissions from Manure Deposition

Where nitrous oxide emissions due to manure deposition are included in the project boundary per Table 3, they are quantified in the baseline scenario under Quantification Approach 3 using Equations (27)–(32).

$$\overline{N2O\_md_{bsl,i,t}} = N2O\_md_{bsl,direct,i,t} + N2O\_md_{bsl,indirect,i,t} \tag{27}$$

Where:

$\overline{N2O\_md_{bsl,i,t}}$ = Areal mean nitrous oxide emissions due to manure deposition in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$N2O\_md_{bsl,direct,i,t}$ = Direct nitrous oxide emissions due to manure deposition in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$N2O\_md_{bsl,indirect,i,t}$ = Indirect nitrous oxide emissions due to manure deposition in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

Direct nitrous oxide emissions due to manure deposition in the baseline scenario are quantified using Equations (28) and (29).

$$\overline{N2O\_md_{bsl,direct,i,t,P,S}} = \frac{\sum_{l=1}^{L} F_{bsl,manure,l,i,t,P} \times EF_{N2O,md,l,S} \times 44/28 \times GWP_{N2O}}{1000 \times A_i} \tag{28}$$

$$F_{bsl,manure,l,i,t,P} = \left[\left(Pop_{bsl,l,i,t} \times Nex_{l,P}\right) \times AWMS_{l,i,t,P,S} \times MS_{bsl,l,i,t}\right] \tag{29}$$

Where:

$\overline{N2O\_md_{bsl,direct,i,t,P,S}}$ = Areal mean direct nitrous oxide emissions due to manure deposition in the baseline scenario for sample unit *i* for productivity system *P* and manure management system *S* in year *t* (t CO_2e/ha)

$F_{bsl,manure,l,i,t,P}$ = Amount of nitrogen in manure and urine deposited on soils by livestock type *l* for productivity system *P* in sample unit *i* in year *t* (kg N)

$Nex_{l,P}$ = Average annual nitrogen excretion per head of livestock type *l* for productivity system *P* (kg N deposited/(head × year))

$EF_{N2O,md,l,S}$ = Emission factor for nitrous oxide from manure and urine deposited on soils by livestock type *l* for manure management system S (kg N_2O-N/kg N input)

$MS_{bsl,l,i,t}$ = Baseline fraction of total annual N excretion for each livestock type *l* for sample unit *i* in year *t* that is deposited on the project area (%)

1000 = Conversion factor from kg to t

Indirect nitrous oxide emissions due to manure deposition in the baseline scenario are quantified under Quantification Approach 3 using Equations (30)–(32).

$$\overline{N2O\_md_{bsl,indirect,i,t}} = (N2O\_md_{bsl,volat,i,t} + N2O\_md_{bsl,leach,i,t})/A_i \tag{30}$$

$$N2O\_md_{bsl,volat,i,t} = F_{bsl,manure,l,i,t,P} \times Frac_{GASM,l,S} \times EF_{Nvolat} \times \frac{44}{28} \times GWP_{N2O} \tag{31}$$

$$N2O\_md_{bsl,leach,i,t} = F_{bsl,manure,l,i,t,P} \times Frac_{LEACH,l,S} \times EF_{Nleach} \times \frac{44}{28} \times GWP_{N2O} \tag{32}$$

Where:

$\overline{N2O\_md_{bsl,indirect,i,t}}$ = Areal mean indirect nitrous oxide emissions due to manure deposition in the baseline scenario for sample unit *i* in year *t* (t CO_2e/ha)

$N2O\_md_{bsl,volat,i,t}$ = Indirect nitrous oxide emissions produced from atmospheric deposition of N volatilized due to manure deposition for sample unit *i* in year *t* (t CO_2e)

$N2O\_md_{bsl,leach,i,t}$ = Indirect nitrous oxide emissions produced from leaching and runoff of N, in regions where leaching and runoff occurs, as a result of manure deposition for sample unit *i* in year *t*. Equal to zero where annual precipitation is less than potential evapotranspiration, unless irrigation is employed (t CO_2e)

8.2.11 Nitrous Oxide Emissions from Biomass Burning

Nitrous oxide emissions from biomass burning in the baseline scenario are quantified under Quantification Approach 3.

Parameter $\overline{N2O\_bb_{bsl,i,t}}$ is estimated using Equation (33).

$$\overline{N2O\_bb_{bsl,i,t}} = \left(\frac{GWP_{N2O} \times \sum_{c=1}^{C} MB_{bsl,c,i,t} \times CF_c \times EF_{c,N2O}}{10^6}\right)/A_i \tag{33}$$

Where:

$\overline{N2O\_bb_{bsl,i,t}}$ = Areal mean nitrous oxide emissions in the baseline scenario from biomass burning for sample unit *i* in year *t* (t CO_2e/ha)

$EF_{c,N2O}$ = Nitrous oxide emission factor for the burning of agricultural residue type *c* (g N_2O/kg dry matter burnt)

10^6 = Conversion factor from grams to tonnes

8.3 Project Emissions

Stock change/emissions resulting from project scenario ALM activities are calculated or modeled based on monitored inputs. Project scenario CO_2, CH_4 and N_2O emissions must be quantified following the approaches found in

Table 5 and using the equations provided in Section 8.2. For all equations, the subscript *bsl* must be substituted by *wp* to make it clear that the relevant values are being quantified for the project scenario. Further, as per Section 8.4.2, where livestock are included in the baseline, the project must use at a minimum the average livestock value from the historical look-back period.

Quantification Approach 1

Model inputs must be collected following the guidance in Table 8.

Table 8: Guidance on collection of model inputs, where required by the model selected, for Quantification Approach 1 for the project scenario

Model Input Category	Timing	Approach
SOC content and bulk density to calculate SOC stocks	Determined at project start via direct measurements at *t* = 0 or (back-) modeled to *t* = 0 from measurements collected within ±5 years of *t* = 0. Subsequent measurements are required every five years or more frequently.	Directly measured via conventional analytical laboratory methods — for example dry combustion or proximal sensing techniques (INS, LIBS, MIR and Vis-NIR) — with known uncertainty, following the criteria in Appendix 4 and VMD0053 guidance. See parameter table for $\overline{SOC_{wp,i,t}}$.

Soil properties (other than bulk density and SOC)	Determined ex ante	Measured or determined from published soil maps with known uncertainty. Estimates from direct measurements must: 1) Be derived from representative (unbiased) sampling; and 2) Ensure accuracy of measurements through adherence to best practices (to be determined by the project proponent and outlined in the monitoring plan).
Climate variables (e.g., precipitation, temperature)	Continuously monitored ex post	Measured for each model-specific meteorological input variable at its required temporal frequency (e.g., daily) for the model prediction interval. Measurements are taken at the closest continuously monitored weather station not exceeding 50 km from the sample field, or from a synthetic weather station (e.g., PRISM[32]).
ALM activities (as identified following procedures in VMD0053, referencing categories of practices outlined in Applicability Condition 1)	Monitored ex post	Required model inputs related to ALM practices will be monitored and recorded for each project year *t*. Information on ALM practices will be monitored via consultation with, and substantiated with a signed attestation from, the farmer or landowner of the sample unit. Any quantitative information (e.g., discrete or continuous numeric variables) on ALM practices must be supported by one or more forms of documented evidence pertaining to the selected sample field and relevant monitoring period (e.g., management logs, receipts or invoices, farm equipment specifications). Units for quantitative information will be based on model input requirements.

Quantification Approach 2

Quantification Approach 2 is used to estimate emissions from SOC stocks only. SOC stocks in the project scenario ($SOC_{wp,i,t}$) are calculated on an equivalent soil mass (ESM) basis by multiplication with the SOC content in each sample unit or stratum at time t – 1, directly measured in each sample field. Where bulk density is measured in a fixed depth approach, mass corrections may be applied to meet the ESM requirement.

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[32] Available at: https://climatedataguide.ucar.edu/climate-data/prism-high-resolution-spatial-climate-data-united-states-maxmin-temp-dewpoint

A detailed description of SOC stock calculations with multiple soil depth increments and spreadsheets and R scripts to standardize and facilitate calculations on an ESM basis are provided in Wendt and Hauser (2013) and von Haden et al. (2020). SOC stock changes are calculated in Equation (40).

Quantification Approach 3

Project emissions are calculated for each sample field using applicable default values and any monitored parameters. The most accurate available emission factor applicable to the project conditions must be used, in the following descending order of preference:

1) Where available, a project-specific emission factor from a peer-reviewed scientific publication[33] must be used.
2) Where there is no relevant peer-reviewed scientific literature, the project proponent may propose alternative sources of information (e.g., government databases, industry publications) to establish the default factor(s) and must provide evidence that the alternative source of information is robust and credible (e.g., independent expert attestation).
3) Where no alternative information source is available that is applicable to the project conditions, projects may derive emission factors using activity data collected during the project by following the guidance to derive Tier 2 emission factors in the respective sections of the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*.
4) Where projects justify a lack of sufficient activity data and project-specific information sources, Tier 1 and Tier 1a emission factors from the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* may be selected.

Woody Biomass

Aboveground woody biomass must be included where project activities may significantly reduce this pool compared to the baseline. In all other cases, aboveground woody biomass is an optional pool. Where included, it is calculated using the CDM A/R tools *Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities* and *Simplified baseline and monitoring methodology for small scale CDM afforestation and reforestation project activities implemented on lands other than wetlands*. Where woody biomass is harvested, projects must calculate the long-term average GHG benefit following the guidance in the latest version of the *VCS Methodology Requirements* Section 3.6 and the latest version of the *VCS Standard* Section 3.2

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[33] As stated in Section 2.5 of the latest version of the *VCS Methodology Requirements*, peer-reviewed scientific literature used to derive (default) emission factors must be in a journal indexed in the Web of Science: Science Citation Index.

8.4 Leakage

Improved ALM projects may result in leakage through: new application of organic amendments from outside the project area (i.e., organic amendments applied in the project from outside of the project area, that were not previously applied in the historical look-back period); productivity declines; displacement of livestock outside of the project boundary; and/or diversion of biomass residues that were used for bioenergy applications in the baseline scenario. Guidance on how to account for each type of leakage is provided below.

As mentioned in Section 5, where the sum of increases in greenhouse gas emissions from any leakage source is less than five percent of the total net anthropogenic GHG emission reductions and removals due to the project, such sources may be deemed de minimis and may be ignored. This demonstration must be conducted via application of the CDM *Tool for testing significance of GHG emissions in A/R CDM project activities.*

8.4.1 Accounting for Leakage from New Application of Organic Amendments from Outside the Project Area

Where new[34] manure, compost or biosolids[35] are applied in the project that were not applied in the historical look-back period, there is a risk of activity shifting leakage. To account for this type of leakage, a deduction must be used unless any of the following apply:

1) The manure or compost applied in the project are produced on-site from farms within the project area;
2) The manure is documented to have been diverted from an uncontrolled anaerobic lagoon, pond, tank or pit[36] from which there is no recovery of methane for generation of heat and/or electricity; or
3) The manure, compost or biosolids are documented to not have been used as a soil amendment.

The deduction represents the portion of manure, compost or biosolids carbon that remains in the project area without degrading and which would have otherwise been applied to agricultural land outside of the project area.

Equation (34) estimates the leakage from imported manure, compost or biosolids that are diverted from other applications and could have led to an increase of SOC outside the project

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[34] In this context, “new” refers to manure application to fields that did not have manure applied during the historical look-back period.

[35] Biosolids are the nutrient-rich organic materials resulting from the treatment of domestic sewage in a wastewater treatment facility (i.e., treated sewage sludge).

[36] Where manure is diverted for field application, rather than stored anaerobically in an uncontrolled lagoon, pond, tank or pit, the avoided methane emissions will far outweigh the SOC impacts. Where manure is temporarily stored prior to field application, the storage should occur under aerobic conditions in stocks or piles. For definitions of manure storage and management systems, refer to Table 10.18 of Chapter 10 of the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

boundary in the absence of the project activity. The total amount of carbon applied is reduced to 12 percent based on the global manure C retention coefficient from Maillard and Angers (2014). This value reflects the fraction of manure carbon expected to remain in project area soils. While derived for manure, the equation is also conservatively applied to compost or biosolids in this methodology.

$$LE_{OA,t} = \sum_{l}\left(M\_manure_{wp,l,t} \times CC_{wp,l,t} \times 0.12 \times \frac{44}{12}\right) \tag{34}$$

Where:

$LE_{OA,t}$ = Leakage from organic amendments in year *t* (t CO_2e)

$M\_OA_{wp,l,t}$ = Mass of organic amendment applied as fertilizer in the project area in year *t* (tonnes)

$CC_{wp,l,t}$ = Carbon content of organic amendment applied as fertilizer in the project area in year *t* (t C/t manure)

0.12 = Fraction of manure (i.e., organic amendment) carbon expected to remain in project area soils (unitless)

$\frac{44}{12}$ = Ratio of molecular weight of carbon dioxide to carbon

8.4.2 Accounting for Leakage from Livestock Displacement

To avoid crediting emission reductions resulting from livestock displacement (i.e., lowering of CH_4 and N_2O emissions within the project area relative to the baseline by reducing the number of livestock within the project boundary), the number of livestock in the project scenario must not be lower than in the historical look-back period. Where livestock displacement occurs, CH_4 and N_2O emissions associated with livestock must continue to be counted in the project scenario (Sections 8.2.7 and 8.2.10) to account for potential emissions leakage.

8.4.3 Accounting for Leakage from Productivity Declines

Market leakage is likely to be negligible because the land remains in agricultural production in the project scenario. Further, producers are unlikely to implement and maintain ALM practices that result in productivity declines, since their livelihoods depend on crop harvests and/or livestock outputs as a source of income. Nevertheless, to ensure leakage is not occurring, the following steps must be completed every 10 years:

Step 1: Demonstrate that the productivity of each crop/livestock product has not declined by more than 5 percent in the project scenario by:

1) Comparing average with-project productivity (excluding years with extreme[37] weather events) during the project period to average baseline productivity during the historical look-back period, by crop/livestock product, using Equation (35).

$$\Delta P = \left(\frac{P_{wp,p} - P_{bsl,p}}{P_{bsl,p}} \right) \times 100 \tag{35}$$

Where:

ΔP = Change in productivity (%)
$P_{wp,p}$ = Average productivity for product p during the project period (output/ha)
$P_{bsl,p}$ = Average productivity for product p during the historical look-back period (output/ha)
p = Crop/livestock product

Or

2) Comparing the ratio of average baseline productivity to average regional productivity during the historical look-back period with the ratio of average with-project productivity to average regional productivity during the project period, by crop/livestock product, using Equation (36) and regional data from government (e.g., USDA Actual Production History (APH) data), industry, peer-reviewed, academic or international organization (e.g., FAO) sources.[38]

$$\Delta PR = \left(\frac{P_{wp,p}}{RP_{wp,p}} - \frac{P_{bsl,p}}{RP_{bsl,p}} \right) \times 100 \tag{36}$$

Where:

ΔPR = Change in productivity ratio per hectare (%)
$P_{wp,p}$ = Average productivity for crop/livestock product p during the project period (output/ha)
$P_{bsl,p}$ = Average productivity for product p during the historical look-back period (output/ha)
$RP_{wp,p}$ = Average regional productivity for product p during the project period (output/ha)

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[37] Extreme weather events are defined as temperature, drought or precipitation events falling in the upper or lower tenth percentile of historical multi-year records for the project location. Tropical storms affecting the project location (e.g., hurricanes, typhoons and cyclones) are also considered extreme weather events, as is any time that a weather-related insurance claim is awarded.

[38] Using this approach, a productivity decline of 10 percent in the project scenario would be acceptable as long as a corresponding productivity decline of 10 percent was also observed in regional data. This ensures that external factors such as reduced rainfall that may impact productivity in a region are fairly accounted for. This approach also prevents unfair penalization of producers whose baseline productivity is lower than regional averages due to lack of access to inputs (e.g., agrochemicals), knowledge or some other factor.

$RP_{bsl,p}$ = Average regional productivity for product p during the historical look-back period (output/ha)

p = Crop/livestock product

New crop/livestock products introduced as part of the project (e.g., new crop in rotation, introduction of livestock) that are not present in the historical look-back period should use regional data sources instead of project-specific data sources to determine historical productivity of the crop/livestock product and set $P_{bsl,p}$ equal to $RP_{bsl,p}$.

With-project productivity averages must be based on data collected in the previous 10 years. Productivity averages must not include data that are more than 10 years old. Where productivity has improved, stayed constant or declined by less than 5 percent for a crop/livestock product, no further action is needed. Where a reduction in productivity of greater than 5 percent is observed in one or more crop/livestock products, complete Step 2 for these products.

Step 2: Determine whether the crop/livestock productivity decline was caused by a short-term productivity decrease by repeating the calculation in Step 1 excluding all data inputs from the first three years of project implementation. Where the with-project productivity of the crop/livestock product with the first three years removed is within 5 percent of the baseline productivity of the same crop/livestock product, no further action is needed.[39] Where a reduction in productivity of greater than 5 percent is still observed in one or more crop/livestock products, complete Step 3 for these products.

Step 3: Determine whether the productivity decline is limited to a certain combination of factors by stratifying the analysis by:

1) Practice change category,
2) Practice change category combinations,
3) Crop type,
4) Soil type, and/or
5) Climatic zone.

Where the productivity decline is limited to a certain combination of factors, that combination becomes ineligible for future crediting. For example, where a 10 percent decline in corn yields was observed and stratification showed that the yield decline was linked to fertilizer rate reductions, rate reduction practices on corn fields would no longer be eligible for future crediting. Where the project proponent is unable to isolate the source(s) of leakage through stratification, the entire crop/livestock product becomes ineligible for future crediting.

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[39] Initial implementation of improved ALM practices may lead to some declines in productivity as the producer adjusts their operation. By demonstrating that productivity in more recent years is within the 5 percent threshold, Step 2 shows that producers have overcome any early productivity declines.

8.4.4 Accounting for Leakage from Diversion of Biomass Residues Used for Energy Applications in the Baseline Scenario

Where manure or crop residue management is a component of the project activity, and the manure or crop residues are diverted from energy applications (e.g., fuel for cookstoves or biomass power generation) in the baseline scenario there is a risk of leakage. Due to the implementation of the project activity, these competing applications might be forced to use inputs which are not carbon neutral. Leakage emissions $LE_{BR,t}$ must be determined following procedures in the CDM *Tool 16: Project and leakage emissions from biomass.*[40]

8.5 Net GHG Emission Reductions and Removals

Net GHG emission reductions are quantified as:

$$\begin{aligned} E_{red,t} = {} & \Delta CO2\_ff_t + \Delta CO2\_lime_t + \Delta CH4\_ent_t + \Delta CH4\_md_t + \Delta CH4\_bb_t \\ & + \left(\Delta CH4\_soil_t \times \left(1 - UNC_{t,CH4\_soil}\right)\right) \\ & + \left(\Delta N2O\_soil_t \times \left(1 - UNC_{t,N2O\_soil}\right)\right) + \Delta N2O\_bb_t \end{aligned} \tag{37}$$

Where:

$E_{red,t}$ = Estimated net GHG emissions reductions in year *t* (t CO_2e)

$\Delta CO2\_ff_t$ = Total carbon dioxide emission reductions from fossil fuel combustion in year *t* (t CO_2e)

$\Delta CO2\_lime_t$ = Total carbon dioxide emission reductions from liming in year *t* (t CO_2e)

$\Delta CH4\_ent_t$ = Total methane emission reductions from livestock enteric fermentation in year *t* (t CO_2e)

$\Delta CH4\_md_t$ = Total methane emission reductions from manure deposition in year *t* (t CO_2e)

$\Delta CH4\_bb_t$ = Total methane emission reductions from avoided or reduced biomass burning in year *t* (t CO_2e)

$\Delta CH4\_soil_t$ = Total methane emission reductions from increasing uptake into the SOC pool in year *t* (t CO_2e)

$UNC_{t,CH4\_soil}$ = Uncertainty deduction in year *t* when using Quantification Approach 1 to model methane emission reductions from increasing uptake into the SOC pool (fraction between 0 and 1)

$\Delta N2O\_soil_t$ = Total nitrous oxide emission reductions from nitrification/denitrification in year *t* (t CO_2e)

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[40] See Section "Leakage due to diversion of biomass residues from other applications" in the latest version of CDM Tool 16.

$UNC_{t,N2O\_soil}$ = Uncertainty deduction in year *t* when using Quantification Approach 1 to model nitrous oxide emission reductions from nitrification/denitrification (fraction between 0 and 1)

$\Delta N2O\_bb_t$ = Total nitrous oxide emission reductions from avoided or reduced biomass burning in year *t* (t CO_2e)

Net GHG emissions removals are quantified as:

$$E_{rem,t} = \left(\left(\Delta CO2_{soil_t} - LE_{OA,t} - LE_{BR,t} \right) \times \left(1 - UNC_{t,CO2} \right) \right) + \Delta C_{TREE,t} + \Delta C_{SHRUB,t} \tag{38}$$

Where:

$E_{rem,t}$ = Estimated net GHG emissions removals in year *t* (t CO_2e)

$\Delta CO2\_soil_t$ = Total carbon dioxide emission removals from increasing the SOC pool in year *t* (t CO_2e)

$LE_{BR,t}$ = Leakage emissions from the diversion of manure or crop residues from baseline energy applications in year *t* (t CO_2e)

$\Delta C_{TREE,t}$ = Total carbon dioxide emission removals from increasing tree biomass in year *t* (t CO_2e)

$\Delta C_{SHRUB,t}$ = Total carbon dioxide emission removals from increasing shrub biomass in year *t* (t CO_2e)

$UNC_{t,CO2}$ = Uncertainty deduction in year *t* associated with modeling or measuring SOC stock changes (fraction between 0 and 1)

Net GHG emission reductions and removals are quantified as:

$$ERR_t = E_{red,t} + E_{rem,t} \tag{39}$$

Where:

$ERR_{n,t}$ = Estimated net GHG emissions reductions and removals in year *t* (t CO_2e)

8.5.1 Carbon Dioxide Emission Reductions and Removals

Carbon dioxide emission removals by enhancing the SOC pool for sample unit *i* in year *t* are quantified using Equation (40).

$$\Delta CO2\_soil_t = \sum_{i=1}^{n} \left(\left(\left(\overline{SOC_{wp,i,t}} - \overline{SOC_{wp,i,t-1}} \right) - \left(\overline{SOC_{bsl,i,t}} - \overline{SOC_{bsl,i,t-1}} \right) \right) \times \frac{44}{12} \right) \times A_i \tag{40}$$

Where:

$\overline{SOC_{wp,i,t}}$ = Areal mean carbon stocks in the SOC pool in the project scenario for sample unit *i* at the end of year *t* (t CO_2e /ha)

$\overline{SOC_{wp,i,t-1}}$ = Areal mean carbon stocks in the SOC pool in the project scenario for sample unit *i* at the end of year *t* − 1 (t CO_2e/ha)

$\overline{SOC_{bsl,i,t}}$ = Areal mean carbon stocks in the SOC pool in the baseline scenario for sample unit *i* at the end of year *t* (t CO_2e/ha)

$\overline{SOC_{bsl,i,t-1}}$ = Areal mean carbon stocks in the SOC pool in the baseline scenario for sample unit *i* at the end of year *t* − 1 (t CO_2e/ha)

The initially measured SOC (at *t* = 0 determined through direct measurements or (back-) modeled to *t* = 0 from measurements collected within ±5 years of *t* = 0) is the same in both the baseline and project scenarios at the outset of the project (i.e., $SOC_{wp,i,0} = SOC_{bsl,i,0}$) for Quantification Approach 1. As a result, the first calculation of Equation (40) for sample unit *i* simplifies to $SOC_{wp,i,t} - SOC_{bsl,i,t}$.

For Quantification Approach 2, carbon dioxide emission removals by enhancing the SOC pool for sample unit *i* in year *t* are compared to the estimated SOC stock change in baseline control sites. The average SOC stock per hectare of each “project site–baseline control site” combination should be used. Where measurements are conducted less frequently than every year, results must be divided by the number of years to calculate an annual SOC stock change.

Carbon dioxide emission reductions from fossil fuel combustion are quantified as:

$$\Delta CO2\_ff_t = \sum_{i=1}^{n} \left(\overline{CO2\_ff_{wp,i,t}} - \overline{CO2\_ff_{bsl,i,t}}\right) \times A_i \tag{41}$$

Where:

$\overline{CO2\_ff_{wp,i,t}}$ = Areal mean carbon dioxide emissions from fossil fuel combustion in the project scenario for sample unit *i* in year *t* (t CO_2e/ha)

Carbon dioxide emission removals in tree biomass are quantified as:

$$\Delta C_{TREE,t} = \sum_{i=1}^{n} \left(\overline{\Delta C_{TREE,wp,i,t}} - \overline{\Delta C_{TREE,bsl,i,t}}\right) \times A_i \tag{42}$$

Where:

$\overline{\Delta C_{TREE,wp,i,t}}$ = Areal mean project scenario carbon stock change in tree biomass for sample unit *i* in year *t* (t CO_2e/ha)

$\overline{\Delta C_{TREE,bsl,i,t}}$ = Areal mean baseline carbon stock change in tree biomass for sample unit *i* in year *t* (t CO_2e/ha)

Carbon dioxide emission removals in shrub biomass are quantified as:

$$\Delta C_{SHRUB,t} = \sum_{i=1}^{n} \left(\overline{\Delta C_{SHRUB,wp,i,t}} - \overline{\Delta C_{SHRUB,bsl,i,t}} \right) \times A_i \tag{43}$$

Where:

$\overline{\Delta C_{SHRUB,wp,i,t}}$ = Areal mean project scenario carbon stock change in shrub biomass for sample unit *i* in year *t* (t CO2e/ha)

$\overline{\Delta C_{SHRUB,bsl,i,t}}$ = Areal mean baseline carbon stock change in shrub biomass for sample unit *i* in year *t* (t CO2e/ha)

Carbon dioxide emission reductions from liming are quantified as:

$$\Delta CO2\_lime_t = \sum_{i=1}^{n} \left(\overline{CO2\_lime_{wp,i,t}} - \overline{CO2\_lime_{bsl,i,t}} \right) \times A_i \tag{44}$$

Where:

$\overline{CO2\_lime_{wp,i,t}}$ = Areal mean carbon dioxide emissions from liming in the project scenario for sample unit *i* in year *t* (t CO2e/ha)

$\overline{CO2\_lime_{bsl,i,t}}$ = Areal mean carbon dioxide emissions from liming in the baseline scenario for sample unit *i* in year *t* (t CO2e/ha)

8.5.2 Methane Emission Reductions ($\Delta CH4_t$)

Methane emission reductions from the SOC pool are quantified as:

$$\Delta CH4\_soil_t = \sum_{i=1}^{n} \left(\overline{CH4\_soil_{bsl,i,t}} - \overline{CH4\_soil_{wp,i,t}} \right) \times A_i \tag{45}$$

Where:

$\overline{CH4\_soil_{bsl,i,t}}$ = Areal mean methane emissions from SOC pool in the baseline scenario for sample unit *i* in year *t* (t CO2e/ha)

$\overline{CH4\_soil_{wp,i,t}}$ = Areal mean methane emissions from SOC pool in the project scenario for sample unit *i* in year *t* (t CO2e/ha)

Methane emission reductions from livestock enteric fermentation are quantified as:

$$\Delta CH4\_ent_t = \sum_{i=1}^{n} \left(\overline{CH4\_ent_{bsl,i,t}} - \overline{CH4\_ent_{wp,i,t}} \right) \times A_i \tag{46}$$

Where:

$\overline{CH4\_ent_{bsl,i,t}}$ = Areal mean methane emissions from livestock enteric fermentation in the baseline scenario for sample unit *i* in year *t* (t CO2e/ha)

$\overline{CH4\_ent_{wp,i,t}}$ = Areal mean methane emissions from livestock enteric fermentation in the project scenario for sample unit *i* in year *t* (t CO2e/ha)

Methane emission reductions from manure deposition are quantified as:

$$\Delta CH4\_md_t = \sum_{i=1}^{n} \left(\overline{CH4\_md_{bsl,i,t}} - \overline{CH4\_md_{wp,i,t}}\right) \times A_i \qquad (47)$$

Where:

$\overline{CH4\_md_{bsl,i,t}}$ = Areal mean methane emissions from manure deposition in the baseline scenario for sample unit *i* in year *t* (t CO2e/ha)

$\overline{CH4\_md_{wp,i,t}}$ = Areal mean methane emissions from manure deposition in the project scenario for sample unit *i* in year *t* (t CO2e/ha)

Methane emission reductions from avoided or reduced biomass burning are quantified as:

$$\Delta CH4\_bb_t = \sum_{i=1}^{n} \left(\overline{CH4\_bb_{bsl,i,t}} - \overline{CH4\_bb_{wp,i,t}}\right) \times A_i \qquad (48)$$

Where:

$\overline{CH4\_bb_{bsl,i,t}}$ = Areal mean methane emissions from biomass burning in the baseline scenario for sample unit *i* in year *t* (t CO2e/ha)

$\overline{CH4\_bb_{wp,i,t}}$ = Areal mean methane emissions from biomass burning in the project scenario for sample unit *i* in year *t* (t CO2e/ha)

8.5.3 Nitrous Oxide Emission Reductions ($\Delta N2O_t$)

Nitrous oxide emission reductions from nitrification/denitrification are quantified as:

$$\Delta N2O\_soil_t = \sum_{i=1}^{n} \left(\overline{N2O\_soil_{bsl,i,t}} - \overline{N2O\_soil_{wp,i,t}}\right) \times A_i \qquad (49)$$

Where:

$\overline{N2O\_soil_{bsl,i,t}}$ = Areal mean nitrous oxide emissions from nitrogen inputs to soils in the baseline scenario for sample unit *i* in year *t* (t CO2e/ha)

$\overline{N2O\_soil_{wp,i,t}}$ = Areal mean nitrous oxide emissions from nitrogen inputs to soils in the project scenario for sample unit *i* in year *t* (t CO2e/ha)

Nitrous oxide emission reductions from biomass burning are quantified as:

$$\Delta N2O\_bb_t = \sum_{i=1}^{n} \left(\overline{N2O\_bb_{bsl,\iota,t}} - \overline{N2O\_bb_{wp,\iota,t}} \right) \times A_i \qquad (50)$$

Where:

$\overline{N2O\_bb_{wp,\iota,t}}$ = Nitrous oxide emissions from biomass burning in the project scenario for sample unit *i* in year *t* (t CO_2e/ha)

8.6 Uncertainty

Uncertainty deductions are estimated separately for each GHG source within a project. Deductions are based on an estimate of the total error of the project's calculated GHG emission reductions or removals for that source over a given verification period. Key sources of uncertainty that contribute to this error differ for each quantification approach. This section details these sources of error and methods to estimate such errors for use in an uncertainty assessment and calculation of the required uncertainty deduction.

Uncertainty guidance provided here assumes that all soil sampling/analysis and modeling occur on a point basis. In other words, the model is run in a manner to represent a single point in space at which initial soil data and management data have been collected, and uncertainty is calculated by combining estimates of sampling, modeling and measurement error based on the design chosen to select the points. Alternative approaches (e.g., modeling on an areal basis) are considered a deviation and project proponents must demonstrate that such approaches will not negatively impact the conservativeness of GHG emissions reduction estimates per the latest version of the *VCS Standard* Section 3.18.

Across quantification approaches a key source of error is sampling error, which emerges from only being able to measure/model a portion of the total project area. Appropriate estimates of this source of error are specific to the sample design employed. Per Section 8.2.1, this methodology requires that stratified random sampling is used as a sample design. Strata should be based on physical and management factors that minimize within-strata variability. Individual sample points are allocated randomly within those strata on a proportional basis by area.

The remainder of this section is based on a simplified example of a stratified random sampling design in which the entire project is divided into strata and points within those strata are placed using simple random sampling with replacement. Examples of additional uncertainty calculations using a multi-stage design potentially applicable in grouped project scenarios are available in Appendix 6. Equations here and in Appendix 6 are provided as examples for possible sample designs expected to be used in projects developed under this methodology. Where a project proponent elects to use an alternative design via a methodology deviation, they must provide a similar demonstration of uncertainty calculations that consider the same sources of error identified here and that are appropriate to the chosen design.

8.6.1 Quantification Approach 1

Quantification Approach 1 is a measure and model approach in which a biogeochemical model is used to simulate changes in SOC stocks and GHG fluxes over a given time period in both the project and baseline scenarios. Initial measures of SOC are taken at the project start[41] for use within the model. SOC is periodically remeasured throughout the project period to true-up modeled estimates of SOC stock changes. Key sources of error accounted for under Quantification Approach 1 include:

- **Model prediction error** resulting from uncertainty in model parameters or model structural errors (i.e., inaccurate representation of actual biogeochemical processes). Model prediction error is calculated using independent validation datasets per the processes outlined in VMD0053. Alternatively, project proponents may account for model prediction error by calibrating models to include parameter uncertainty (e.g., a Bayesian implementation of the model) and using the Monte Carlo (MC) simulation or error propagation approach detailed below.
- **Sampling error** resulting from measuring/modeling only a portion of the project area. Estimates of sampling error are contingent on the sampling design employed by the project proponent.
- **Measurement error** of model inputs (see Table 6), including initial SOC content, bulk density, soil texture and management data, where applicable. In many cases, the impact of these measurement errors on the error of ERR estimates is assumed to be captured in model prediction error and/or sampling error (see Section 8.6.1.2.2 for additional details). Where alternative approaches for measuring SOC content, such as soil spectroscopy techniques, are used, procedures for estimation of measurement error of these techniques as outlined in Appendix 6 must be followed. In this case, MC simulation is required unless it is demonstrated that such errors have a de minimis effect on model estimates of ERRs.

For each carbon pool or GHG flux, these sources of error are estimated separately and then combined to estimate a single uncertainty deduction for that carbon pool or GHG flux across the entire project. Two approaches are eligible to estimate the uncertainty:

1) Analytical calculation of error propagation; or
2) Monte Carlo (MC) simulation.

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[41] Initial measurements of SOC may be conducted at $t = 0$ or (back-) modeled to $t = 0$ from measurements collected within ±5 years of $t = 0$.

8.6.1.1 Analytical Calculation of Error Propagation

In this approach, the various sources of error outlined above are independently estimated for each GHG source or carbon pool • that results in an ERR (e.g., SOC, N_2O). The estimated errors are then combined to provide an estimate of the total variance of the areal mean emissions reduction across the project for each source in each verification period ($s^2_{\Delta\bullet,t}$). This is used to determine an appropriate uncertainty deduction.

8.6.1.1.1 Model Prediction Error

Model prediction error includes model structural error (i.e., parameter uncertainty) and any errors related to model data inputs (e.g., inaccuracy of source for soil texture data), which result in incorrect estimation of a flux or change in stock in either the project or baseline scenarios or both. Model prediction error is quantified by using a validation dataset that includes ground-truth measurements of stock changes or fluxes for the baseline and project scenario practices. Differences between these ground-truth measurements and model simulations of the same locations/practices are calculated, and assuming the model is unbiased, model prediction error is captured by the variance of these errors.

The ideal validation dataset would come from controlled experimental field trials in which practices that simulate a project scenario are used in one part of the field and practices that simulate a baseline scenario are used in another part of the same field. Then, errors of the project minus baseline emissions of a certain gas or pool, Δ•, are computed directly at each site *i* using $error_{\Delta\cdot,i} = \widehat{\Delta\bullet}_i - \Delta\bullet_i$. The model uncertainty is estimated as the variance of $error_{\Delta\bullet,i}$ across all sites in the validation dataset. Validation data come from experiments that range in duration from a few years to many decades, and model prediction error at each point is derived from simulations that match the durations of those experiments. This means that these errors will necessarily represent the accumulated model error over varying time intervals. When estimating model prediction error for verification, model error from a single verification period – which may range from one to five years – is required and is likely to be smaller than the raw mean squared validation error.

For verification periods shorter than the median length of experiments in the validation dataset, a single mixed-duration estimate of model prediction error is conservative and acceptable to use at verification. For example, where a model is validated against a dataset containing experiments with lengths of 2, 2, 3, 5, 9 and 48 years, the error from this validation dataset may be applied to any simulation of length four years or shorter.

Where insufficient data are available to use the approach described above, quantification of model error may be split into two separate tasks:

1) Model predictions and ground truth measurements may be used to estimate typical errors of the prediction of emissions in one scenario (e.g., just the project scenario), and
2) The correlation of errors between project and baseline scenarios may be estimated from a more limited number of side-by-side field trials such as those described above.

Assuming that the variance of the model prediction is the same in the project and baseline scenarios (i.e., $s^2_{model,\bullet,pr} = s^2_{model,\bullet,bsl}$ which is denoted by $s^2_{model,\bullet}$), then:

$$s^2_{model,\Delta\bullet} = s^2\left(\widehat{\Delta\bullet}_{bsl} - \widehat{\Delta\bullet}_{pr}\right) = 2\left[s^2_{model,\bullet} - cov(\widehat{\Delta\bullet}_{pr},\widehat{\Delta\bullet}_{bsl})\right] \tag{51}$$

Where:

$s^2_{model,\Delta\bullet}$ = Variance of modeled estimates of emission reductions in gas or pool • (t CO$_2$e/ha)^2
$\widehat{\Delta\bullet}_{bsl}$ = Modeled estimate of change in emissions reductions in gas or pool • in the baseline scenario (t CO$_2$e)
$\widehat{\Delta\bullet}_{pr}$ = Modeled estimate of change in emissions reductions in gas or pool • in the project scenario (t CO$_2$e)
$s^2_{model,\bullet}$ = Estimated variance of errors made by model prediction of emissions in gas or pool • (estimated from measurements in fields that need not be side-by-side trials with baseline and project scenarios) (t CO$_2$e/ha)^2

By writing $cov(\widehat{\Delta\bullet}_{pr},\widehat{\Delta\bullet}_{bsl})$ in terms of a correlation coefficient:

$$\rho = \frac{cov(\widehat{\Delta\bullet}_{pr},\widehat{\Delta\bullet}_{bsl})}{\sqrt{(s^2_{model,\bullet\,pr})(s^2_{model,\bullet\,bsl})}} \tag{52}$$

Then:

$$s^2_{model,\Delta\bullet} = 2\, s^2_{model,\bullet}\,(1-\rho)$$

Where:

ρ = Correlation of errors in project and baseline scenario pairs (estimated from side-by-side field trials of baseline and project scenarios)

Note – See parameter tables in Section 9.2 for derivation of $\bar{\Delta}_{\bullet,t}$ *and* $\bar{\bullet}_t$

Because side-by-side trials are rare, ρ is estimated from fewer data points than $s^2_{model,\bullet}$. In the initial stages of a project, it is expected that the datasets used to estimate model prediction error will be the same as those used to validate the model, following the procedures outlined in VMD0053. As the project proceeds and SOC stocks in the project scenario are periodically remeasured, those data should be used to update the estimate of model prediction error for the SOC pool (see Section 8.6.1.3 for additional details). For other GHG fluxes that are modeled under Quantification Approach 1 (e.g., N_2O, CH_4), model prediction error should continue to be based on the use of validation datasets but may be updated as new validation datasets become available that match the criteria outlined in VMD0053.

Within a project, it is possible that different model prediction errors may be applicable to different portions of the project area. For example, a project may include areas where a cover crop is being implemented, and others where reduced tillage is being implemented, representing two different project scenarios for which model prediction error may differ. Similarly, a project may span a geographic area with varied climate and/or soil types across which model prediction error may differ. In such cases, different model prediction error terms most appropriate to a given sampling unit should be selected, and an aggregate estimate of model prediction error across the entire project must be determined using an estimator appropriate to the design.

8.6.1.1.2 Model Input and Measurement Error

The ALM data used as model inputs may be an important source of error where details of such activities are not well known. However, as projects are expected to follow the data collection procedures outlined in Box 1 to determine ALM activities across the entire project area, this source of error is assumed to be sufficiently minor. Similarly, uncertainty related to estimation of area is considered to be negligible provided that GIS boundaries of the project area are accurately delineated and that the necessary QA/QC procedures to remove irrelevant features (i.e., streams, pavement, areas not under improved management, etc.) outlined in the parameter table for A_i are followed.

Measurement error of physical properties (e.g., precipitation, soil texture) used as model inputs may also be a source of error, although it has generally been found to be less significant compared to model structural error (Ogle et al., 2010; Peltoniemi et al., 2006). Provided that measurement errors in model inputs translate to measurement errors in model predictions that are uncorrelated across sample points, these errors are automatically captured by the estimate of sample error discussed below[42]. Similarly, for inputs such as precipitation, which are the same across baseline and project scenarios and for which estimates are retrieved for a given point from the same data source (e.g., GIS data products, digital soil maps), the influence of such measurement error on estimates of ERRs is captured in the estimate of model prediction error generated through model calibration/validation procedures. These procedures are described in the preceding section and in VMD0053. Remeasurement and true-up provide additional opportunities to refine these error estimates.

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[42] See, for example, Cochran (1977, p. 382); de Gruijter et al. (2006, p. 82); Som (1995, p. 438)

Where soil spectroscopy tools are used in place of conventional analytical techniques to determine SOC content at sampling points, it must not be assumed that measurement error from such methods is automatically captured in the estimate of model prediction error or that the impact of such errors is negligible. Soil spectroscopy methods may have high measurement error under different circumstances and may be biased (i.e., error differs depending on the carbon content of the sample under consideration and the coverage of datasets used to calibrate/validate the soil spectroscopy model). Biogeochemical models are sensitive to initial starting SOC content, meaning error in estimates will have a non-linear impact on model simulations of both the baseline and project scenarios. Therefore, where soil spectroscopy is used to determine SOC content data for use as an input to biogeochemical models, the MC simulation approach must be used, unless project proponents demonstrate that measurement error from the tool used is unbiased and has a de minimis impact on model simulations.

Where uncertainty of ALM data or measurement error of other input data types is considered to have an impact on modeled estimates of ERRs despite use of best practices in data collection, the MC simulation method for error propagation should be used.

8.6.1.1.3 Sampling Error

Sampling error derives from only measuring or modeling a subset of the entire project area, resulting in a potentially inaccurate estimate of the true variance of a GHG flux or carbon stock change. Sampling error is determined by calculating the approximate standard error of GHG fluxes or carbon stock changes as simulated by the model for a given monitoring period. The uncertainty estimator used must be based on the sampling design employed. All examples provided here assume that the default approach of measuring/modeling on a point basis is employed. Where alternative approaches are proposed via a methodology deviation, project proponents must provide evidence that the design is unbiased and must document use of the correct uncertainty estimator to capture sampling error (see also Section 8.2.1).

This section is based on a stratified random sampling design in which the entire project is divided into strata and points are randomly allocated (with replacement) within the strata. Soil samples are collected at these points and the model is run. Formulae for uncertainty estimators are drawn from Som (1995, Ch. 10). Additional examples are provided in Appendix 6. As stated in Section 8.2.1.2, project-specific strata, their area and the sampling points within strata must be reported in a spreadsheet and submitted as an annex to project documentation at every verification. This information will feed into Equation (53) for the parameters stratum identifier (*h*), area of stratum (A_h) and sample point identifier (*ip*).

$$s^2_{sampling,\Delta\bullet,t} = \sum_{h=1}^{H} s^2_{sampling,\Delta\bullet,h,t} \tag{53}$$

Where:

$$s^2_{sampling,\Delta\bullet,h,t} = \frac{A_h^2}{n_h(n_h-1)}\sum_{ip=1}^{n_h}\left(\Delta\bullet_{h,ip,t} - \overline{\Delta\bullet_{h,t}}\right)^2$$

and:

$s^2_{sampling,\Delta\bullet,t}$ = Variance of emission reductions in gas or pool • due to sampling error at time *t* across the entire project area (t CO_2e)^2

$s^2_{sampling,\Delta\bullet,h,t}$ = Variance of emission reductions in gas or pool • within stratum *h* due to sampling error at time *t* (t CO_2e)^2

$\overline{\Delta\bullet_{h,t}}$ = Areal mean emissions reduction in gas or pool • in stratum *h* at time *t*, computed as the average across the sample points in stratum *h* (t CO_2e/ha)

$\Delta\bullet_{h,ip,t}$ = Estimated emissions reduction of gas or pool • on an area basis in year *t* in stratum *h* at point *ip* (t CO_2e/ha)

h = 1, …, *H* strata across the entire project area

ip = 1, …, n_h sample points within stratum *h*

A_h = Area of stratum *h*

8.6.1.1.4 Combined Sample and Model Error

To incorporate model errors, assume that they are uncorrelated with the input data in the sample and are independent across samples. Then, the variance of $\overline{\Delta\bullet_t}$ incorporating sample uncertainty and model prediction uncertainty is estimated by combining the variance estimates of both error sources divided by the square of the total project area (Cochran, 1977 Eq. 13.39; Som, 1995 Eq. 25.10). Note that only the estimate of sampling error is divided by the square of the project area in this example as it is presumed that model prediction error has already been determined on an area basis per Equation (51)-(52).

$$s^2_{\overline{\Delta\bullet},t} = \frac{s^2_{sampling,\Delta\bullet,t}}{A^2} + s^2_{model} \tag{54}$$

Where:

$s^2_{\overline{\Delta\bullet},t}$ = Variance of the estimate of mean emission reductions from gas or pool • at time *t* (t CO_2e/ha)^2

s^2_{model} = Variance of the estimate of emission reductions in gas or pool • due to model prediction error (t CO_2e/ha)^2

A = Total project area

Lastly, s^2_{model} is an estimate of average variance of model prediction errors across the project and is estimated using an estimator appropriate to the project sampling design. In this example, it is assumed that the model prediction error value for each stratum is selected based on the specific project and baseline scenarios being implemented in that stratum and as such s^2_{model} is estimated using an area-weighted uncertainty estimator.

$$s_{model}^2 = \sum_{h=1}^{H} \frac{A_h^2}{A^2} s_{model,h}^2 \tag{55}$$

8.6.1.2 Monte Carlo Simulation

In addition to the analytical error propagation method detailed in Section 8.6.1.1, a Monte Carlo (MC) simulation method may be used for uncertainty estimation. MC simulation methods are commonly used in Bayesian analyses, which have gained popularity as a framework for estimating uncertainty of outputs from process-based biogeochemical models of soils and agroecosystems and estimating the uncertainty of biogeochemical model predictions (Gurung et al., 2020; Kennedy and O'Hagan, 2001). MC simulation methods are suitable for nonlinear, deterministic, process-based biogeochemical models (e.g., DayCent, DNDC). Unlike the analytical error propagation method, the MC method more easily addresses key dependencies in underlying data (such as correlation between model parameters) and asymmetric error distributions (such as non-negative or highly skewed distributions). The MC method is used in the USDA's approach for estimating emissions at the farm scale (Eve et al., 2014) and in the US National GHG Inventory (US EPA, 2021). The approach is also described in peer-reviewed literature (Gurung et al., 2020; Ogle et al., 2007, 2010).

For each sample point, a set of L random samples (total number of MC simulations) is drawn from a posterior predictive distribution (PPD) produced by the model. Within each sample unit, the total set of PPDs across all points are then aggregated to determine the areal mean unbiased estimator of the ERR estimates being evaluated and the uncertainty of those estimates. Random samples may also be taken from probability distribution functions of model input data, particularly where those inputs have measurement error that is not accounted for in the model validation process.

To generate a PPD, Bayesian calibration methods must be used to estimate model parameters as probability distribution functions (as opposed to single values). To ensure parity with the analytical error propagation method detailed in Section 8.6.1.1, these probability distribution functions of model parameters must be determined per the model calibration/validation guidance in VMD0053 using external datasets representative of the project area and activities or, in the case of SOC, using remeasured project SOC stocks (see Section 8.6.1.3). In other words, the likelihood function from which the PPD is sampled must be based on the same dataset against which the model is validated. Steps to calibrate and validate a model for use with the MC uncertainty propagation method must be documented in a model validation report following the guidance in VMD0053.

Since many biogeochemical models include dozens of parameters, it is not expected that all parameters are calibrated as probability distribution functions. Instead, a more limited number of parameters may be used for MC simulation, for instance identified through sensitivity analysis. In the simplest implementation, a single parameter representing residual model prediction error may be used. In such cases, the MC simulation method is implemented using a "meta-model" that represents uncertainty in the chosen set of parameters but does not necessarily require direct modification of model source code. Kennedy and O'Hagan (2001) provide additional detail on relevant calibration methods and Gurung et al. (2020) provide an example of such methods being specifically implemented for a soil biogeochemical model. Gelman et al. (2014) is a useful reference on Bayesian statistical methods and provides additional detail on definitions of PPDs and valid methods to generate them.

The notation in this section is different than in previous sections, aligning with notation commonly used in Bayesian statistics. Key differences include:

- The observed outcome of interest (i.e., GHG ERRs) is denoted as y, which is commonly used in statistics to denote outcomes.
- MC draws of model-predicted GHG ERRs are denoted as $\tilde{y}$. The tilde serves as a reminder that $\tilde{y}$ is a model prediction drawn from a PPD (following standard notation in Gelman et al. 2014; Hoff, 2009) due to the use of Bayesian calibration (Kennedy and O'Hagan, 2001).
- Total GHG ERRs and areal mean GHG ERRs are denoted as τ and μ, respectively, in keeping with Thompson (2012). The use of lowercase Greek letters is also a reminder that it is not possible to directly observe the estimand of interest (true total and areal mean GHG ERRs) due to measurement error.
- The notation in this section suppresses notation for monitoring period t for convenience and to avoid confusion with the Greek character τ (total GHG ERRs) which is used throughout.
- *Var* is used in place of s^2 in multiple locations to signify variance to more easily match Equation (59), which describes how variance is broken down into sampling and modeling error.

8.6.1.2.1 Combined Sample and Model Error

For a particular time period and GHG emission source, the estimand, or target parameter of interest, is the true total GHG ERRs across the entire project, denoted as τ, in tonnes of carbon dioxide equivalent (t CO$_2$e). The estimate of τ produced through MC simulation is denoted by $\hat{\tau}$. Similarly, the areal mean ERR is denoted by μ (equivalent to $\Delta \bullet_t$) in t CO$_2$e/ha. Estimates of μ are denoted as $\hat{\mu}$. Since model prediction error is implicitly incorporated into the MC simulations through parameter uncertainty, these estimates may then be used to estimate sampling and model prediction error based on the realized sample s and the sampling design employed. Here, an example of this process is provided, using the same stratified random sample design demonstrated in Section 8.6.1. Additional examples are provided in Appendix 6.

First, to generate an estimate ($\hat{\tau}$) of τ, GHG emissions are simulated under the baseline and project scenarios multiple times at each sample point, indexed by $l = 1, \ldots, L$. The GHG ERRs at each point are then calculated as the difference between predicted GHG emissions under baseline and project scenarios. These estimates are used to produce an estimate of GHG ERRs ($\tilde{y}$) at each point, similarly indexed by l following Equation (56) below.

$$\tilde{y}_{hil} = \tilde{z}_{bsl,h,ip,l} - \tilde{z}_{wp,h,ip,l} \tag{56}$$

Where:

$\tilde{y}_{hil}$ = Predicted GHG emissions reduction on an area basis for point *i* in stratum *h* and MC simulation l (t CO2e/ha)

$\tilde{z}_{bsl,h,ip,l}$ = Predicted GHG emissions in the baseline scenario on an area basis for point *ip* in stratum *h* and MC simulation l (t CO2e/ha)

$\tilde{z}_{wp,h,ip,l}$ = Predicted GHG emissions in the project scenario on an area basis for point *ip* in stratum *h* and MC simulation l (t CO2e/ha)

l = 1, ..., *L* MC simulations

Note – notation for the source of emissions and time period is suppressed. The sign convention is that $\tilde{z}_{bsl,hil}$ is emissions to the atmosphere in the baseline scenario. Thus, for the SOC pool, $\tilde{z}_{bsl,hil}$ is −1 times the predicted temporal change in SOC stocks in the baseline scenario. Similarly, $\tilde{z}_{wp,hil}$ is −1 times the predicted temporal change in the project scenario.

The total set of *L* estimates of $\tilde{y}$ are then used to produce $\hat{\tau}$ and $\hat{\mu}$, according to Equation (57).

$$\hat{\mu} = \frac{\hat{\tau}}{A} \tag{57}$$

Where:

$$\hat{\tau} = \sum_{h=1}^{H} \hat{\tau}_h$$

$$\hat{\tau}_h = \frac{A_h}{n_h L} \sum_{ip=1}^{n_h} \left(\sum_{l=1}^{L} \tilde{y}_{h,ip,l} \right)$$

And:

$\hat{\tau}$ = Monte Carlo estimate (MC mean) of total GHG emissions reductions for a given source across the whole project area (t CO2e)

$\hat{\mu}$ = Areal mean unbiased estimator of emissions reductions for gas or pool • in year *t* (t CO2e/ha)

$\hat{\tau}_h$ = Monte Carlo estimate (MC mean) of GHG emissions reductions for a given source within stratum *h* (t CO2e)

The total uncertainty is then decomposed into two components, sampling and modeling uncertainty. Using standard variance decomposition (i.e., the law of total variance) following Del Grosso et al. (2010), the total variance is decomposed according to Equation (58).

$$\mathrm{Var}(\hat{\tau}) = \mathbb{E}[\mathrm{Var}(\hat{\tau}|\boldsymbol{s})] + \mathrm{Var}(\mathbb{E}[\hat{\tau}|\boldsymbol{s}]) \tag{58}$$

Where:

$\mathbb{E}[\mathrm{Var}(\hat{\tau}|\boldsymbol{s})]$ = Estimate of model uncertainty (i.e., expectation of the conditional variance given the sample design)

$\mathrm{Var}(\mathbb{E}[\hat{\tau}|\boldsymbol{s}])$ = Estimate of the uncertainty due to sampling design (i.e., the variance of the conditional expectation)

s = The realized sample, selected using the sample design

For the stratified random sampling design used in this example, the variance components are estimated according to the following system of equations. Note that these are similar in form to those in Section 8.6.1 and are derived from Som (1995, Ch. 10).

$$\widehat{Var}(\hat{\tau}) = s^2_{sampling} + s^2_{model} = \left\{\sum_{h=1}^{H} s^2_{sampling,h}\right\} + s^2_{model} \tag{59}$$

Where:

$$s^2_{sampling,h} = \frac{A_h^2}{n_h(n_h-1)}\sum_{ip=1}^{n_h}\left(\hat{y}_{h,ip} - \hat{\mu}_h\right)^2$$

$$\hat{y}_{h,ip} = \frac{1}{L}\sum_{l=1}^{L}\tilde{y}_{h,ip,l}$$

$$\hat{\mu}_h = \frac{\hat{\tau}_h}{A_h}$$

And:

$$s^2_{model} = \frac{1}{L-1}\sum_{l=1}^{L}(\tilde{\tau}_l - \hat{\tau})^2$$

$$\tilde{\tau}_l = \sum_{h=1}^{H}\tilde{\tau}_{hl}$$

$$\tilde{\tau}_{hl} = \frac{A_h}{n_h}\sum_{ip=1}^{n_h}\tilde{y}_{h,ip,l}$$

And:

$s^2_{sampling}$	=	Variance of emission reductions in gas or pool • due to sampling error at time *t* (notation suppressed) across the entire project area (t CO_2e)^2
$s^2_{sampling,h}$	=	Variance of emission reductions in gas or pool • within stratum *h* due to sampling error at time *t* (notation suppressed) (t CO_2e)^2
$\tilde{\tau}_l$	=	Total GHG emission reductions for the lth MC simulation of the project (t CO_2e)
$\tilde{\tau}_{hl}$	=	Total GHG emission reductions in stratum *h* for the lth MC simulation (t CO_2e)
$\hat{y}_{h,ip}$	=	MC estimate of areal mean GHG emission reductions for point *ip* in stratum *h* (t CO_2e/ha)
$\hat{\mu}_h$	=	MC estimate of areal mean GHG emission reductions in stratum *h* (t CO_2e/ha)

Last, the variance of the average GHG ERRs $\left(\widehat{\mathrm{Var}}(\hat{\mu})\right)$ is obtained by dividing $\widehat{\mathrm{Var}}(\hat{\tau})$ by the square of the total project area (A^2).

$$\widehat{Var}(\hat{\mu}) = s^2_{\Delta\bullet} = \frac{s^2_{sampling} + s^2_{model}}{A^2} \tag{60}$$

Note that in Equations (59)–(60), the sampling variance may be calculated separately for each stratum and then summed together, because the sampled points are selected independently in different strata (see Theorems 5.1 and 5.2 of Cochran, 1977, pp. 91–92). In contrast, model prediction errors may not be independent across strata due to shared calibration parameters. Thus, estimation of model variance must not be split across strata and is instead estimated across the entire project area. Also, note that unlike in Equation (54), the model prediction error (s^2_{model}) must be divided by the square of the project area because in this example it is estimated on the basis of total GHG ERRs achieved across the entire project area.

8.6.1.2.2 Monte Carlo Propagation of Model Input Error

Monte Carlo error propagation methods may be used in some cases to propagate model input errors alone. Note that in Section 8.6.1.2 these errors are identified as being otherwise captured in estimates of sample or model prediction error. However, in some circumstances, such as when land management data are uncertain or soil spectroscopy tools are used to measure initial SOC, these errors may not be captured in those terms. MC error propagation is appropriate in such cases and need not require recalibration of soil model parameters. In such cases, the measurement errors are propagated to the sampling error term, which should be determined according to the procedures outlined in Equations (56)–(59) that relate to sampling error. For example, MC simulations would entail sampling from a PPD of estimated SOC content for a given point based on a chosen soil spectroscopy method (see Appendix 4 for additional details), and those values would be used to initialize the process-based model. Model prediction error may be determined using either the analytical error propagation method or the MC simulation method and is added to the estimate of sampling error to provide an estimate of the total uncertainty for a given emissions reduction.

8.6.1.2.3 Monte Carlo Error

The accuracy of the MC estimates depends on the number of independent MC draws. Where MC draws use a Markov Chain Monte Carlo (MCMC) algorithm such as the No-U-Turn Sampler implemented in Stan (Carpenter et al., 2017), samples may contain some autocorrelation and thus the MC error depends on an effective sample size that is smaller than the initial number of chosen draws. The MC error (errors due to using a finite number of MC draws) decreases with increasing number of MC draws. According to Gelman et al. (2014, p. 267), the contribution of MC error to MC estimates of standard error is $\sqrt{1+1/L}$. For L = 100 independent MC draws, MC error would inflate the standard error by a factor of only 1.005, implying that the MC error adds almost nothing to the uncertainty estimation. More than 100 simulations may add numerical stability to estimates, particularly for the percentile summaries. Gelman et al. (2014) suggest a choice of L between 100 and 2000. A value between 500 and 1000 is suggested to balance accuracy and computing power demand.

8.6.1.3 Remeasurement, Model True-Up and Cumulative Crediting

As outlined in Section 8.3, SOC stocks must be directly remeasured every five years in the project scenario. These data are used to re-estimate model prediction error and/or recalibrate the model in relation to measured SOC stocks.

Prior to remeasurement, model structural error during simulation of SOC stocks for initial model validation will be based solely on the procedures outlined in VMD0053. Specifically, the model is used to simulate changes in stocks from a set of selected external datasets (i.e., field trials for which data have been previously collected). Following remeasurement, data from external datasets and remeasurement are combined to create a new calibration/validation dataset which is used as follows:

1) Where the analytical error propagation method is used, data on remeasured stocks should be used to re-estimate model prediction error following the procedures outlined in Section 8.6.1.1. Since the baseline scenario is modeled under Quantification Approach 1, remeasured stocks may only be used to update estimates of error for the project scenario. Equations (51) and (52) should be followed, in which the correlation coefficient of model errors in the baseline and project scenarios determined at initial model validation is used to adjust the model prediction error estimate.

2) Where the Monte Carlo error propagation method is used, remeasured SOC stocks should be used to update the probability distribution functions of model parameters/hyperparameters using the same approach as was applied at initial model validation as per VMD0053.

Following model true-up via either procedure outlined above, proponents should rerun model simulations for both the baseline and project scenarios from t_0 up to present day and recalculate uncertainty deductions to be applied to future credit vintages. VCUs that have been issued in previous verifications will remain unchanged.

8.6.2 Quantification Approach 2

Quantification Approach 2 is applicable for SOC stocks only. The baseline is represented by control sites that are linked to one or more project sample units. The SOC stock difference and its uncertainty is calculated based on comparisons of control sites and paired project sample units. Key sources of error accounted for under Quantification Approach 2 include:

- **Sampling error** resulting from measuring/modeling only a portion of the project area.
- **Measurement error** of methods used to determine SOC stock equivalents (t CO_2e per unit area) at sample points. Where samples are collected using equivalent soil mass approaches and analyzed using dry combustion via a lab with demonstrated proficiency and quality control (e.g., through participation in the North American Proficiency Testing program[43]), these errors are assumed to be unbiased and negligible. Where alternative measurement approaches such as soil spectroscopy techniques are used, measurement error must be estimated and propagated through estimates of the total change in SOC.

These sources of error are estimated separately and then combined to estimate a single uncertainty deduction for SOC stocks across the entire project. Similar to Quantification Approach 1, an analytical error propagation or MC simulation method may be used. The MC simulation method is only applicable in cases where measurement error is deemed significant and must be propagated through calculations.

As in Section 8.6.1, an example is provided here based on the default stratified random sampling approach. In this example, each individual stratum is paired with an appropriately determined control site. Net SOC stock changes in the project scenario are determined by comparing net change in SOC in project sites against net change in baseline control sites over a given verification period *t*, determined through direct sampling and dry combustion analysis of soil samples collected at the beginning and end of period *t*. It is assumed that the same set of sample points are visited at both time points.

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[43] Available at: https://www.naptprogram.org/

The total variance of the SOC stock change estimate is then determined using an area-weighted uncertainty estimator based on the variance of SOC stock change estimates in each stratum. Variance of SOC stock change estimates in each stratum are based on the combined variance of the estimates of change over time in a given verification period *t* for both the project and baseline scenarios. The covariance of these estimates is conservatively excluded as the baseline control sites and project sites are assumed to be independent. Note that in these equations Δ is used to signify emissions reduction in the SOC pool (i.e., project scenario SOC stocks minus baseline scenario SOC stocks) and changes in SOC stocks over time in both the baseline and project scenarios.

$$s^2_{\overline{\Delta SOC,t}} = \frac{1}{A^2}\sum_{i=1}^{n} s^2_{\Delta SOC,h,t} \tag{61}$$

Where:

$$s^2_{\Delta SOC,h,t} = s^2_{\Delta SOC,wp,h,t} + s^2_{\Delta SOC,bsl,h,t}$$

And:

$s^2_{\overline{\Delta SOC,t}}$ = Variance of the estimate of mean SOC stock changes in verification period *t* across the entire project area, calculated as the difference in net change between the project and baseline scenarios over period *t* (t CO_2e/ha)^2

$s^2_{\Delta SOC,h,t}$ = Variance of the estimate of total SOC stock changes in verification period *t* in stratum *h*, calculated as the difference in net change between the project and baseline scenarios over period *t* (t CO_2e)^2

$s^2_{\Delta SOC,wp,h,t}$ = Variance of the estimate of total SOC stock changes in the project plots in verification period *t* in stratum *h*, calculated as the difference in SOC stocks at the beginning and end of period *t* (t CO_2e)^2

$s^2_{\Delta SOC,bsl,h,t}$ = Variance of the estimate of total SOC stock changes in baseline (control) plots paired with project stratum *h* in verification period *t*, calculated as the difference in SOC stocks at the beginning and end of period *t* (t CO_2e)^2

Note that the area-weighting in Equation (61) is based on the area of the project strata, not the baseline control sites with which they are paired.

Because the sample design for the project and baseline control plots may be different, the uncertainty estimator should match the sample design used in the project and baseline control plots. For example, the project area may be monitored using a staged design if there are a substantial number of sampling units (e.g., fields) in the project area. But the baseline control plots may be fewer, meaning they can all be monitored and would not require a staged design. In such cases, baseline and project areas should use different uncertainty estimators before estimating the combined uncertainty. However, this example presumes that within each stratum, sample points are similarly determined using simple random sampling with replacement for both baseline and project scenarios, so the estimator in both scenarios should be the same.

Equation (62) provides an example for the project scenario. The variance of the estimate of the change is then a function of the variance and covariance of soil sampling results at both time points within verification period *t*. These time points are denoted as t_{final} and t_{start}, hereafter shortened to subscripts *f* and *s*.

$$s^2_{\Delta SOC,wp,h,t} = s^2_{SOC,wp,h,f} + s^2_{SOC,wp,h,s} - 2COV\left(SOC_{wp,h,f}\ ;\ SOC_{wp,h,s}\right) \tag{62}$$

Where:

$$s^2_{SOC,wp,h,f} = \frac{A_h^2}{n_h(n_h-1)}\sum_{i=1}^{n_h}\left(SOC_{wp,h,ip,f} - \overline{SOC}_{wp,h,f}\right)^2$$

$$s^2_{SOC,wp,h,s} = \frac{A_h^2}{n_h(n_h-1)}\sum_{ip=1}^{n_h}\left(SOC_{wp,h,ip,s} - \overline{SOC}_{wp,h,s}\right)^2$$

$$COV\left(SOC_{wp,h,f}\ ;\ SOC_{wp,h,s}\right) = \frac{A_h^2}{n_h(n_h-1)}\sum_{ip=1}^{n_h}\left(SOC_{wp,h,ip,s} - \overline{SOC}_{wp,h,s}\right)\left(SOC_{wp,h,ip,f} - \overline{SOC}_{wp,h,f}\right)$$

And:

$s^2_{SOC,wp,h,f}$ = Variance of the estimate of SOC stocks in the project scenario at t_{final} in stratum *h* (t CO_2e)^2

$s^2_{SOC,wp,h,s}$ = Variance of the estimate of SOC stocks in the project scenario at t_{start} in stratum *h* (t CO_2e)^2

$COV\left(SOC_{wp,h,f}\ ;\ SOC_{wp,h,s}\right.$ = Covariance of estimates of SOC stocks at t_{final} and t_{start} in the project scenario in stratum *h* (t CO_2e)^2

$\overline{SOC}_{wp,h,f}$ = Mean estimate of SOC stocks across all points in the project scenario at t_{final} in stratum *h* (t CO_2e/ha)

$\overline{SOC}_{wp,h,s}$ = Mean estimate of SOC stocks across all points in the project scenario at t_{start} in stratum *h* (t CO_2e/ha)

$SOC_{wp,h,ip,f}$ = Estimate of SOC stock on an area basis at point *ip* in the project scenario at t_{final} in stratum *h* (t CO_2e/ha)

$SOC_{wp,h,ip,s}$ = Estimate of SOC stock on an area basis at point *ip* in the project scenario at t_{start} in stratum *h* (t CO_2e/ha)

8.6.2.1 Alternative SOC Measurement Methods

Projects may elect to use alternative measurement methods to determine SOC content at each sample point, such as Vis-NIR and MIR (see Appendix 4). Such methods may reduce sampling error by allowing for data collection at a greater number of points. However, they introduce error into the estimation of ERRs through the model used to estimate SOC based on reflectance/absorbance data from the chosen instrument. This error is handled using MC simulation methods similar to those in Quantification Approach 1. The value of SOC at each point is iteratively resampled *L* times from a PPD derived from a soil spectroscopy model calibrated and validated on an independent dataset appropriate to the project area. Alternatively, the project proponent may estimate the error of the spectroscopy model by selecting 10–15 percent of samples in the project, analyzing these samples using dry combustion methods, and comparing those results to the spectroscopy model predictions. See Appendix 4 for additional detail on how these models should be calibrated and validated, as well as how PPDs should be developed where an MC simulation approach is pursued.

In either case, uncertainty is estimated using a similar overall form as the procedures outlined in Equations (61) and (62), but the uncertainty estimators in Equation (62) for estimating uncertainty within an individual stratum are modified to include both sampling error and model error from the soil spectroscopy model. Equation (63) provides an example using the MC simulation approach for the project scenario in a given stratum *h*. Individual estimates of SOC content at each soil sampling point are sampled from a PPD *L* times and compared to the mean estimate of SOC across all *L* simulations to generate uncertainty estimates.

$$s^2_{\Delta SOC,wp,h,t} = s^2_{SOC,wp,h,f} + s^2_{SOC,wp,h,s} - 2COV(SOC_{wp,h,f}\,;\,SOC_{wp,h,s}) \qquad (63)$$

The variance of an individual stratum is estimated as follows. The same equation form applies to time point s.

$$s^2_{SOC,wp,h,f} = s^2_{SOC,wp,h,f,sample} + s^2_{SOC,wp,h,f,model}$$

$$s^2_{SOC,wp,h,f,sample} = \frac{A_h^2}{n_h(n_h-1)}\sum_{ip=1}^{n_h}\left(SOC_{wp,h,ip,f} - \overline{SOC}_{wp,h,f}\right)^2$$

$$SOC_{wp,h,ip,f} = \frac{1}{L}\sum_{l=1}^{L} SOC_{wp,h,ipf,l}$$

$$\overline{SOC}_{wp,h,f} = \frac{1}{A_h}\sum_{ip=1}^{n_h} SOC_{wp,h,ip,f}$$

$$s^2_{SOC,wp,h,f,model} = \frac{1}{L-1}\sum_{l=1}^{L}\left(SOC_{wp,f,l} - \overline{SOC}_{wp,f}\right)^2$$

$$SOC_{wp,f,l} = \sum_{h=1}^{H} SOC_{wp,h,f,l}$$

$$SOC_{wp,h,f,l} = \frac{A_h}{n_h} \sum_{ip=1}^{n_h} SOC_{wp,h,f,ip,l}$$

$$\overline{SOC}_{wp,f} = \frac{1}{L} \sum_{l=1}^{L} SOC_{wp,f,l}$$

$$COV\left(SOC_{wp,h,f}\ ;\ SOC_{wp,h,s}\right) = \frac{1}{L} \sum_{l=1}^{L} \left\{ \frac{A_h^2}{n_h(n_h - 1)} \sum_{ip=1}^{n_h} \left(SOC_{wp,h,ip,sl} - \overline{SOC}_{wp,h,s}\right) \left(SOC_{wp,h,ip,f,l} - \overline{SOC}_{wp,h,f}\right) \right\}$$

Where:

$s^2_{SOC,wp,h,f,sample}$ = Variance of the estimate of SOC stocks in the project scenario at t_{final} in stratum h attributable to sampling error (t CO_2e)^2

$s^2_{SOC,wp,h,f,model}$ = Variance of the estimate of SOC stocks in the project scenario at t_{final} in stratum h attributable to prediction error of the soil spectroscopy model (t CO_2e)^2

$\overline{SOC}_{wp,h,f,l}$ = Mean estimate of SOC stocks across all points in the project scenario at t_{final} in stratum h in the lth simulation (t CO_2e/ha)

$SOC_{wp,h,ip,f,l}$ = Estimate of SOC stocks on an area basis at point ip in the project scenario at t_{final} in stratum h in the lth simulation (t CO_2e/ha)

$SOC_{wp,f,l}$ = Estimate of total SOC stocks on an area basis in the project scenario across the entire project at t_{final} in the lth simulation (t CO_2e)

$\overline{SOC}_{wp,f}$ = Mean estimate of total SOC stocks in the project scenario across the entire project at t_{final} averaged across all L simulations (t CO_2e)

Where a project proponent elects not to use the MC simulation approach and instead estimate model error using a simple frequentist approach, then $s^2_{SOC,wp,hf,model}$ in Equation (63) is replaced with an estimate of model prediction error that is the same across all strata and both scenarios, $s^2_{SOC,model}$. This estimate is determined by comparing modeled estimates of SOC to values determined through laboratory analysis (Appendix 4).

$$s^2_{SOC,model} = \frac{A^2}{tvd - 1} \sum_{pvd=1}^{tvd} \left(error_j - mean\ error\right)^2 \tag{64}$$

$$error_{pvd} = SOC_{model,pvd} - SOC_{observed,pvd}$$

$$mean\ error = \frac{1}{tvd} \sum_{pvd=1}^{tvd} error_{pvd}$$

Where:

$s^2_{SOC,model}$ = Variance of the estimate of SOC stocks attributable to prediction error of the soil spectroscopy model (t CO_2e)^2

$error_{pvd}$ = Difference between the predicted estimate of SOC on an area basis and observed SOC at point *pvd* in the randomly selected validation dataset (t CO_2e/ha)

$mean\ error$ = Mean of all estimates of $error_j$ across all *tvd* points in the validation dataset (t CO_2e/ha)

$SOC_{model,pvd}$ = Predicted estimate of SOC on an area basis at point *pvd* in the randomly selected validation dataset (t CO_2e/ha)

$SOC_{observed,pvd}$ = Observed SOC on an area basis at point *pvd* in the randomly selected validation dataset, determined through conventional lab analysis and field sampling (t CO_2e/ha)

pvd = 1, …, *tvd* sample points within the validation dataset

Furthermore, $s^2_{SOC,wp,hf,sample}$ should be determined using the same equation as is used to determine $s^2_{SOC,wp,h,f}$ in Equation (62), but individual point values are instead the value for that point as predicted by the soil spectroscopy model.

8.6.2.2 Extensions to Other Sampling Designs

Note that in this simplified example, it is assumed that a single control plot or area is sufficient to represent the baseline scenario for each stratum and that it is possible to revisit the same soil sampling points at both time points. In practice, such assumptions may not hold true in many projects developed under this methodology. Nonetheless, the overall process for estimating the total variance of the estimate of change should be similar to the example provided above. Equations used to estimate the individual component terms are likely to differ. As with Quantification Approach 1, an additional example is provided in Appendix 6 based on a multi-stage sampling design where stratified random sampling is employed at the final stage when determining location of sampling points.

8.6.3 Quantification Approach 3

In Quantification Approach 3, GHG ERRs are estimated using emission factors (EF) determined to be most relevant for the project area (see Section 8.3 for additional details on EF selection).

While these EFs likely include some prediction error, availability of source data for estimating that error may be inconsistent. As such, the prediction error of EFs is presumed to be zero for the purposes of calculating an uncertainty deduction. Project proponents are required to use the available EF that results in the most conservative GHG ERR estimation when applied across both the baseline and project scenarios.

It is expected that management data will be collected across all sampling units in the project area according to the hierarchy outlined in Box 1, and as such sampling error does not factor into uncertainty deductions. However, where it is not possible to collect management data across the entire project area, sampling error must be accounted. In this case, the procedures for estimating sampling error in Quantification Approach 1 must be followed. The uncertainty estimators must be based on the sampling design used. Project proponents must provide a description of the sampling design and a justification as to why management data are not collected across all sampling units.

8.6.4 Uncertainty Deductions

Uncertainty deductions are estimated and applied separately for each ERR source within the project boundary. This deduction is estimated using a probability of exceedance method as follows (see the latest version of the *VCS Methodology Requirements* Section 2.4):

$$UNC_{\overline{\Delta\cdot},t} = Uncertainty \times t_{\alpha=0.666} \tag{65}$$

$$Uncertainty = \frac{\sqrt{s^2_{\overline{\Delta\cdot},t}}}{\overline{\Delta\cdot}_t} \times 100$$

Where:

$UNC_{\overline{\Delta\cdot},t}$ = Uncertainty deduction for gas or pool • to be applied in verification period *t* (%)

Uncertainty = Half-width of the one standard deviation interval as a percentage of the mean of the ERR estimate for gas or pool • in verification period *t* (%)

$\overline{\Delta\cdot}_t$ = Mean estimated emissions reduction for gas or pool • across the entire project area in year *t* (t CO_2e/ha)

$s^2_{\overline{\Delta\cdot},t}$ = Variance of the estimate of mean emission reductions from gas or pool • at time *t*. See Figure 3 to determine how this is estimated based on the methods employed in the project (t CO2e/ha)[2]

$t_{\alpha=0.666}$ = Critical value of a one-sided student's t-distribution at significance level α = 0.666 (66.6%) with degrees of freedom appropriate to the sampling design used. Equal to approximately 0.4307 at large sample sizes (dimensionless)

This uncertainty deduction is based on a defined threshold in the estimated probability density function of the ERR for a given source. This enables a judgement of the extent to which the achieved removal or reduction by the project may be expected to be accurate. By this procedure, one estimates what percentage of the estimates of $\overline{\Delta \cdot}_t$ would have a 66.6 percent probability of exceeding the true value of $\overline{\Delta \cdot}_t$. That percentage is then used as the uncertainty deduction. Figure 3 demonstrates this concept.

Figure 3: Probability of exceedance. The value for $\overline{\Delta \cdot}_t$ used in calculation of VCUs issued is determined by applying an uncertainty deduction based on the 33.3rd percentile of the estimated probability distribution of $\overline{\Delta \cdot}_t$

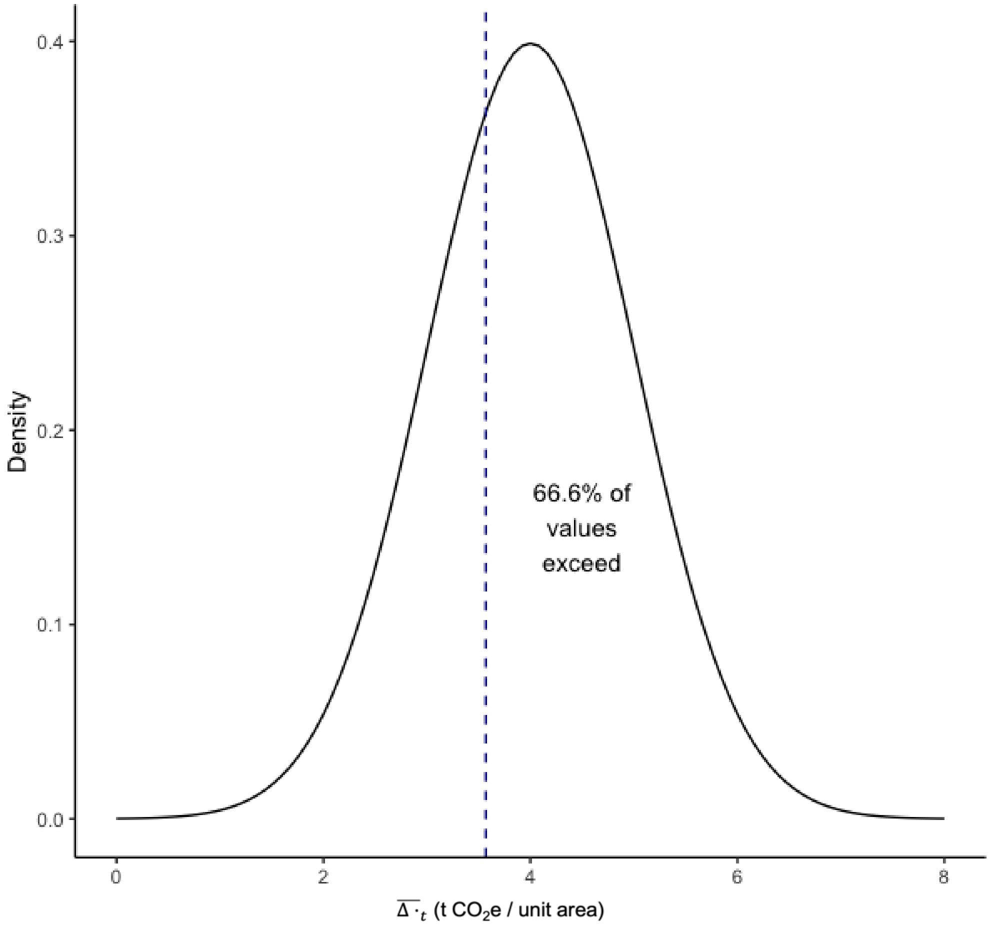
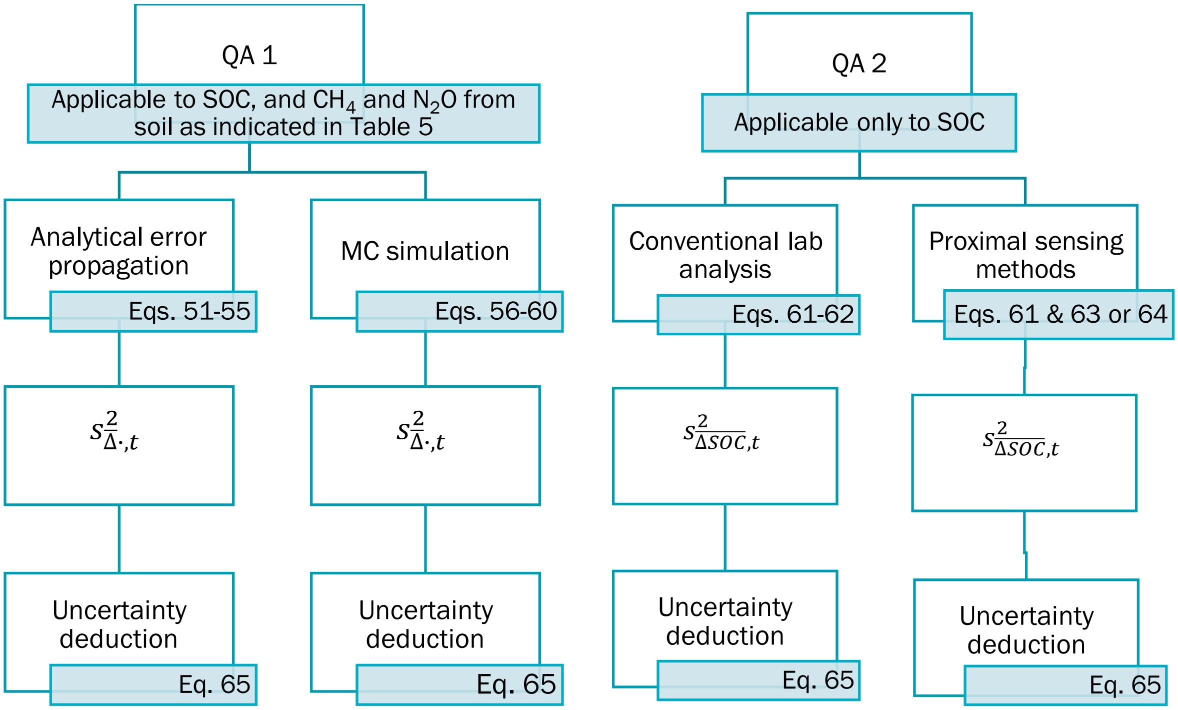


Figure 4: Equation map for calculating uncertainty deduction under Quantification Approaches 1 (for SOC, CH_4 and N_2O) and 2 (for SOC)[44]



8.7 Calculation of Verified Carbon Units

To calculate the number of Verified Carbon Units (VCUs) that may be issued, the project proponent must consider the number of buffer credits which must be deposited in the AFOLU pooled buffer account. The number of buffer credits that must be deposited is calculated by multiplying the non-permanence risk rating[45] by the net change in carbon stocks (see Section 3.8 in the latest version of the *VCS Methodology Requirements*). The net change in carbon stocks is the sum of the net carbon dioxide removals resulting from the net increase in SOC, tree biomass and shrub biomass carbon pools (see Equation (38) in Section 8.5). Therefore, the buffer deduction applies only to the estimated net GHG emissions removals in Equation (66).

The number of VCUs that may be issued in year *t* is calculated as:

$$VCU_t = E_{red,t} + (E_{rem,t} - Buffer_t) \tag{66}$$

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[44] Note that where a sample design other than the default stratified random sampling approach (see Section8.2.1) is proposed via a methodology deviation, these equations should not be used but the general workflow is the same.

[45] As determined by the *AFOLU Non-Permanence Risk Tool*

Where:

VCU_t = Number of VCUs in year *t* (t CO_2e)

$Buffer_t$ = Number of buffer credits to be contributed to the AFOLU pooled buffer account in year *t* (t CO_2e)

9 MONITORING

Where discretion exists in the selection of a value for a parameter, the principle of conservativeness must be applied (see the latest version of the *VCS Standard*).

Box 1: Sources of qualitative and quantitative data

Sources of information for all undefined activity/management-related model input variables (see Table 6 and Table 8), and parameters $FFC_{bsl,j,i,t}$, $Pop_{bsl,l,i,t,P}$, $M_{bsl,SF,i,t}$, $M_{bsl,OF,i,t}$ and $MB_{g,bsl,i,t}$ relevant to the baseline, must follow the requirements detailed below.

All qualitative information on ALM practices must be determined via consultation with, and substantiated with a signed attestation from, the farmer or landowner of the sample field during that period. Where the farmer or landowner is not able to provide qualitative information (e.g., a sample field is newly leased), the project proponent must follow the quantitative information hierarchy outlined below.

The following list specifies the allowable sources of quantitative information on ALM practices in descending order of preference, as available:

1) Historical management records supported by one or more forms of documented evidence pertaining to the selected sample field and period $t = -1$ to $t = -3$ (e.g., management logs, receipts or invoices, farm equipment specifications, logs or files containing machine and/or sensor data) or remote sensing (e.g., satellite imagery, manned aerial vehicle footage, drone imagery), where requisite information on ALM practices may be reliably determined with these methods (e.g., tillage status, crop type, irrigation)
2) Historical management plans supported by one or more forms of documented evidence pertaining to the selected sample field and period $t = -1$ to $t = -3$ (e.g., management plan, recommendations in writing solicited by the farmer or landowner from an agronomist). Where more than one value is documented in historical management plans (e.g., where a range of application rates are prescribed in written recommendations), the principle of conservativeness must be applied and the value that results in the lowest expected emissions (or highest rate of stock change) in the baseline scenario must be selected.
3) A signed attestation from the farmer or landowner of the sample field during that period – where the attested value does not deviate significantly from other evidence-supported values for similar fields (e.g., fertilizer data from adjacent fields with the same crop, adjacent years of the same field, government data on application rates in that area or statement from a local extension agent regarding local application rates). The VVB must determine whether the data are sufficient. In circumstances where this requirement is not met, Option 4 must be followed.
4) Regional (sub-national) average values derived from agricultural census data or other sources from within the 20-year period preceding the project start date or the 10 most recent iterations of the dataset, whichever is more recent. Where estimates have been disaggregated by relevant crop or ownership classes, those should be used. The estimates must be substantiated with a signed attestation from the farmer or landowner of the sample field during that period. Examples include the USDA National Agricultural Statistics Service Quick Stats database and USDA Agricultural Resource Management Survey.

This hierarchy applies to any additional quantitative inputs required by the model (Quantification Approaches 1 and 2) or default factor (Quantification Approach 3) selected. The principle of conservativeness must be applied in all cases.

9.1 Data and Parameters Available at Validation[46]

Data/Parameter	AR
Data unit	Percent
Description	Weighted mean adoption rate
Equations	(1)
Source of data	Calculated for the project across the group or all activity instances
Value applied	Must be less than or equal to 20 percent
Justification of choice of data or description of measurement methods and procedures applied	See Section 7
Purpose of data	Common practice assessment
Comments	Note that grouped projects must include one or more sets of eligibility criteria for the inclusion of new project activity instances ensuring that new project activity instances have characteristics with respect to additionality that are consistent with the initial instances for the specified project activity and geographic area (see latest version of the *VCS Standard*).

Data/Parameter	EA_{ay}
Data unit	Percent
Description	Adoption rate of the *y* most common (by area covered) proposed project activity in the region
Equations	(1)
Source of data	Publicly available information contained in agricultural census or other government (e.g., survey) data, peer-reviewed scientific literature, independent research data or reports/assessments compiled by industry associations. Where all of the above sources are unavailable, a signed and dated attestation statement from a qualified independent local expert.
Value applied	Conditional on data source

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[46] Parameters are listed in order of appearance in the respective equations.

Justification of choice of data or description of measurement methods and procedures applied	See "Source of data" and Section 7
Purpose of data	Common practice assessment
Comments	Note that grouped projects must include one or more sets of eligibility criteria for the inclusion of new project activity instances ensuring that new project activity instances have characteristics with respect to additionality that are consistent with the initial instances for the specified project activity and geographic area (see latest version of the *VCS Standard*).

Data/Parameter	$Area_{ay}$
Data unit	Hectare (ha)
Description	Area of proposed project-level adoption of activity *ay*
Equations	(1)
Source of data	Farm records and project activity commitments
Value applied	Proposed project-level adoption of activity *ay*
Justification of choice of data or description of measurement methods and procedures applied	See Section 7
Purpose of data	Common practice assessment
Comments	Any significant features such as rock piles, waterways or other features not under management must be subtracted from the area estimate. Note that grouped projects must include one or more sets of eligibility criteria for the inclusion of new project activity instances ensuring that new project activity instances have characteristics with respect to additionality that are consistent with the initial instances for the specified project activity and geographic area (see latest version of the *VCS Standard*). Other units used to determine area (e.g., acres) must be converted to hectares.

Data/Parameter	*ay*
Data unit	unitless

Description	Proposed project activity commitments *a*1 to *ay*, where *a*1 covers the largest area in the project region
Equations	(1)
Source of data	Documentation of activities (intended farm management change, for example target fertilizer application rate) to be implemented in the project for each sample unit
Value applied	Dependent on project activities
Justification of choice of data or description of measurement methods and procedures applied	See "Source of data" and Section 7
Purpose of data	Common practice assessment, basis for parameters $Area_{ay}$ and PA_{ay}
Comments	Appendix 1 lists the main categories of practices expected to enhance SOC stocks and/or reduce GHG emissions from soils under a broad range of cropping and livestock systems. This list is non-exhaustive. Note that grouped projects must include one or more sets of eligibility criteria for the inclusion of new project activity instances ensuring that new project activity instances have characteristics with respect to additionality that are consistent with the initial instances for the specified project activity and geographic area (see latest version of the *VCS Standard*).

Data/Parameter	$FFC_{bsl,j,i,t}$
Data unit	Liters
Description	Consumption of fossil fuel type *j* (gasoline or diesel) for sample unit *i* in year *t* in the baseline scenario
Equations	(8)
Source of data	See Box 1
Value applied	See Box 1
Justification of choice of data or description of measurement methods and procedures applied	Fossil fuel consumption may be monitored or the amount of fossil fuel combusted may be estimated using fuel efficiency (e.g., l/100 km, l/t-km, l/hour) of the vehicle and the appropriate unit of use for the selected fuel efficiency (e.g., km driven where efficiency is given in l/100 km).
Purpose of data	Calculation of baseline emissions

Comments	Peer-reviewed published data may be used to determine fuel efficiency. For example, fuel efficiency factors may be obtained from Chapter 3, Volume 2 of IPCC (2019).

Data/Parameter	$M_{Limestone,bsl,i,t}$ and $M_{Dolomite,bsl,i,t}$
Data unit	tonnes/year
Description	Amount of calcitic limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) applied to sample unit *i* in year *t* in the baseline scenario
Equations	(10)
Source of data	See Box 1
Value applied	Amount of calcic limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) applied to sample unit *i* in year *t*
Justification of choice of data or description of measurement methods and procedures applied	All limestone and dolomite applied to soils should be included, even the proportion applied in mixture with fertilizers. Use of oxides (e.g., CaO) and hydroxides of lime for soil liming is not required to be included in the calculations to estimate CO_2 emissions from liming. Because these materials do not contain inorganic carbon, CO_2 is not released following soil application; it is only produced during material manufacture.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$Pop_{bsl,l,i,t,P}$
Data unit	Head
Description	Population of grazing livestock of type *l* in the baseline scenario in sample unit *i* for productivity system *P* in year *t*
Equations	(12), (13), (29)
Source of data	See Box 1
Value applied	See Box 1
Justification of choice of data or description of measurement methods and procedures applied	Record of number of grazing livestock by type
Purpose of data	Calculation of baseline emissions

Comments	None

Data/Parameter	GWP_{CH4}
Data unit	t CO_2e/t CH_4
Description	Global warming potential for CH_4
Equations	(11)–(13), (15)
Source of data	*IPCC Fifth Assessment Report* (IPCC, 2013)
Value applied	28
Justification of choice of data or description of measurement methods and procedures applied	See "Source of data." Global warming potential values must be applied as described in the latest version of the *VCS Standard* and derived from IPCC Assessment Reports.
Purpose of data	Calculation of baseline and project emissions
Comments	None

Data/Parameter	$W_{bsl,l,i,t,P}$
Data unit	kg animal mass/head
Description	Average weight in the baseline scenario of livestock type *l* for sample unit *i* in productivity system *P* in year *t*
Equations	(14)
Source of data	See Box 1. Where project proponents are able to justify a lack of sufficient activity data and project-specific information sources, Tier 1 values from Table 10A.5, Chapter 10, Volume 4 in IPCC (2019) may be selected.
Value applied	See "Source of data"
Justification of choice of data or description of measurement methods and procedures applied	See "Source of data"
Purpose of data	Calculation of project emissions
Comments	None

Data/Parameter	$MB_{bsl,c,i,t}$
Data unit	kg
Description	Mass of agricultural residues of type *c* burned in the baseline scenario for sample unit *i* in year *t*
Equations	(15), (33)
Source of data	See Box 1
Value applied	See Box 1
Justification of choice of data or description of measurement methods and procedures applied	Peer-reviewed published data may be used to estimate the aboveground biomass prior to burning.
Purpose of data	Calculation of baseline emissions
Comments	Mass of residues burned is a function of the amount of aboveground biomass, the removal of aboveground biomass and whether remaining residues are burned. It is assumed that 100 percent of aboveground biomass is burned in the baseline scenario.

Data/Parameter	GWP_{N2O}
Data unit	t CO_2e/t N_2O
Description	Global warming potential for N_2O
Equations	(16), (19), (23)–(25), (28), (31)–(33)
Source of data	*IPCC Fifth Assessment Report* (IPCC, 2013)
Value applied	265
Justification of choice of data or description of measurement methods and procedures applied	See “Source of data.” Global warming potential values must be applied as described in the latest version of the *VCS Standard* and derived from IPCC Assessment Reports.
Purpose of data	Calculation of baseline and project emissions
Comments	None

Data/Parameter	$M_{bsl,SF,i,t}$
Data unit	t fertilizer
Description	Mass of N-containing synthetic fertilizer type *SF* applied in sample unit *i* in year *t* in the baseline scenario
Equations	(20)
Source of data	See Box 1
Value applied	See Box 1
Justification of choice of data or description of measurement methods and procedures applied	See Box 1
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$M_{bsl,OF,i,t}$
Data unit	t fertilizer
Description	Mass of N-containing organic fertilizer type *OF* applied in the baseline scenario for sample unit *i* in year *t*
Equations	(21)
Source of data	See Box 1
Value applied	See Box 1
Justification of choice of data or description of measurement methods and procedures applied	See Box 1
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$MB_{g,bsl,i,t}$
Data unit	t dm

Description	Annual aboveground and belowground dry matter of N-fixing species *g* returned to soils in the baseline scenario for sample unit *i* in year *t*
Equations	(26)
Source of data	See Box 1
Value applied	See Box 1
Justification of choice of data or description of measurement methods and procedures applied	See Box 1
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$MS_{bsl,l,i,t}$
Data unit	Fraction of N deposited
Description	Fraction of nitrogen excretion by livestock type *l* that is deposited in sample unit *i* in year *t* in the baseline scenario
Equations	(29)
Source of data	See Box 1
Value applied	See Box 1
Justification of choice of data or description of measurement methods and procedures applied	The fraction of nitrogen deposited on the project area is determined based on the amount of time spent grazing on the project area during year *t* for each livestock type *l*. In the absence of data available according to Box 1 (or to conservatively reduce the effort of project development), a value of 1 may be applied with no additional support. This would conservatively assume that livestock deposit 100 percent of their excreted N on the project area for the entirety of year *t*.
Purpose of data	Calculation of baseline and project emissions
Comments	None

Data/Parameter	$P_{bsl,p}$
Data unit	Output (e.g., kg)/ha

Description	Average productivity for product *p* during the historical look-back period
Equations	(35), (36)
Source of data	See Box 1
Value applied	See Box 1
Justification of choice of data or description of measurement methods and procedures applied	Average productivity for each livestock/crop product following guidance in Section 8.4.3
Purpose of data	Determination of baseline productivity for future market leakage analysis
Comments	None

Data/Parameter	$RP_{bsl,p}$
Data unit	Output (e.g., kg)/ha
Description	Average regional productivity for product *p* during the historical look-back period
Equations	(36)
Source of data	Secondary evidence sources of regional productivity (e.g., peer-reviewed literature, industry associations, international databases, government databases)
Justification of choice of data or description of measurement methods and procedures applied	Average regional productivity for each livestock/crop product following guidance in Section 8.4.3
Purpose of data	Determination of baseline productivity ratio for future market leakage analysis
Comments	None

Data/Parameter	A
Data unit	Hectare (ha)
Description	Project area
Equations	(54), (57), (59), (61)

Source of data	Measured in project area
Value applied	The project area is measured prior to validation.
Justification of choice of data or description of measurement methods and procedures applied	Delineation of the project area may use a combination of GIS coverages, ground survey data, remote imagery (satellite or aerial photographs) and other appropriate data. Any imagery or GIS datasets used must be geo-registered referencing corner points, landmarks or other intersection points.
Purpose of data	Calculation of baseline and project emissions
Comments	Other units used to determine project area (e.g., acres) must be converted to hectares.

9.2 Data and Parameters Monitored

Data/Parameter	*MDD*
Data unit	t CO_2e/ha
Description	Minimum detectable difference in SOC stocks between two points in time
Equations	(2), (3)
Source of data	Estimation of the smallest difference in SOC stocks between two monitoring events that may be detected as statistically significant
Description of measurement methods and procedures to be applied	See Section 8.2.1
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1 and further guidance in FAO (2019)
Purpose of data	Development of sampling strategy for baseline setting and measurements for monitoring
Calculation method	See Section 8.2.1
Comments	Calculation of the number of samples required to detect a minimum difference is optional.

Data/Parameter	S
Data unit	Dimensionless
Description	Standard deviation of the difference in SOC stocks between t_0 and t_1
Equations	(2), (3)
Source of data	Estimation of the smallest difference in SOC stocks between two monitoring events that may be detected as statistically significant
Description of measurement methods and procedures to be applied	See Section 8.2.1
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1 and further guidance in FAO (2019)
Purpose of data	Development of sampling strategy for baseline setting and measurements for monitoring
Calculation method	See Section 8.2.1
Comments	Calculation of the number of samples required to detect a minimum difference is optional.

Data/Parameter	n
Data unit	Dimensionless
Description	Number of samples required to detect a minimum difference
Equations	(2), (3)
Source of data	Estimation of the smallest difference in SOC stocks between two monitoring events that may be detected as statistically significant
Description of measurement methods and procedures to be applied	See Section 8.2.1
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1 and further guidance in FAO (2019)
Purpose of data	Development of sampling strategy for baseline setting and measurements for monitoring

Calculation method	See Section 8.2.1
Comments	Calculation of the number of samples required to detect a minimum difference is optional.

Data/Parameter	$n - 1$
Data unit	Dimensionless
Description	Degrees of freedom for the relevant t-distribution
Equations	(2), (3)
Source of data	Estimation of the smallest difference in SOC stocks between two monitoring events that may be detected as statistically significant
Description of measurement methods and procedures to be applied	See Section 8.2.1
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1 and further guidance in FAO (2019)
Purpose of data	Development of sampling strategy for baseline setting and measurements for monitoring
Calculation method	See Section 8.2.1
Comments	Calculation of the number of samples required to detect a minimum difference is optional.

Data/Parameter	$t_{x,u}$
Data unit	Dimensionless
Description	Values of the t-distribution given a certain power level (1 − b) and a significance level
Equations	(2), (3)
Source of data	Estimation of the smallest difference in SOC stocks between two monitoring events that may be detected as statistically significant
Description of measurement methods and procedures to be applied	See Section 8.2.1

Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1 and further guidance in FAO (2019)
Purpose of data	Development of sampling strategy for baseline setting and measurements for monitoring
Calculation method	See Section 8.2.1
Comments	Calculation of the number of samples required to detect a minimum difference is optional.

Data/Parameter	$M_{n,dl,SOC}$
Data unit	kg/ha
Description	SOC mass in soil sample *n* in depth layer *dl*
Equations	(4)
Source of data	Measured after soil sampling in the project area
Description of measurement methods and procedures to be applied	See Section 8.2.1
Frequency of monitoring/recording	Measurement of SOC stocks must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1 Soil mass must not include particles greater than 2 mm in diameter (i.e., gravel/stones) nor plant material. Beem-Miller et al. (2016) provide a useful approach to ensuring high-quality sampling in rocky agricultural soils.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Wendt and Hauser (2013) and von Haden et al. (2020) provide spreadsheets or R scripts to standardize and facilitate calculations of SOC stock calculations with multiple soil depth increments
Comments	None

Data/Parameter	$M_{n,dl,sample}$
Data unit	g

Description	Soil mass of sample n in depth layer dl
Equations	(4)
Source of data	Measured after soil sampling in the project area
Description of measurement methods and procedures to be applied	See Section 8.2.1
Frequency of monitoring/recording	Measurement of SOC stocks must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1 Soil mass must not include particles greater than 2 mm in diameter (i.e., gravel/stones) nor plant material. Beem-Miller et al. (2016) provide a useful approach to ensuring high-quality sampling in rocky agricultural soils.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Mass of gravel/stones and plant material must be subtracted from the sample mass to obtain soil mass.
Comments	None

Data/Parameter	D
Data unit	mm
Description	Inside diameter of probe or auger
Equations	(4)
Source of data	Measured as part of project monitoring
Description of measurement methods and procedures to be applied	Information from product specifications of probe or auger
Frequency of monitoring/recording	Measurement of SOC stocks must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1
Purpose of data	Calculation of baseline and project emissions

Calculation method	Not applicable
Comments	None

Data/Parameter	N
Data unit	Unitless
Description	Number of cores sampled
Equations	(4)
Source of data	Measured in the project area
Description of measurement methods and procedures to be applied	The number of samples taken is determined as part of the development of a sampling strategy (see Section 8.2.1).
Frequency of monitoring/recording	Measurement of SOC stocks must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$OC_{n,dl}$
Data unit	g/kg
Description	Organic carbon content in sample *n* from depth layer *dl*
Equations	(4), (5)
Source of data	Measured in the project area
Description of measurement methods and procedures to be applied	When measuring SOC content via conventional analytical laboratory methods, the use of dry combustion is recommended over other techniques. Emerging technologies (INS, LIBS, MIR and Vis-NIR) with known uncertainty may be applied to measure SOC concentration following the criteria in Appendix 4.

Frequency of monitoring/recording	Measurements of SOC stocks must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	BD_{corr}
Data unit	g/cm^3
Description	Corrected bulk density of the fine soil fraction (after subtracting the mass proportion of the coarse fragments)
Equations	(5)
Source of data	See VMD0053 for bulk density data requirements for model calibration and validation
Description of measurement methods and procedures to be applied	See "Source of data"
Frequency of monitoring/recording	At least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Section 8.2.1.3 and 8.2.1.5 for general sampling and measurement guidance relevant for bulk density data
Purpose of data	Determination of baseline scenario, calculation of baseline and project emissions
Calculation method	Fine soil fraction mass minus mass proportion of the coarse fragments
Comments	Only required when following Quantification Approach 1 for SOC stock changes

Data/Parameter	d
Data unit	cm
Description	Soil depth
Equations	(5)

Source of data	See VMD0053 for requirements on calibration datasets
Description of measurement methods and procedures to be applied	Soil depth for each depth increment to be captured as part of data collection following requirements in VMD0053
Frequency of monitoring/recording	At least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See VMD0053 for requirements on calibration datasets
Purpose of data	Determination of baseline scenario, calculation of baseline and project emissions
Calculation method	Not applicable
Comments	Only required when following Quantification Approach 1 for SOC stock changes

Data/Parameter	$f(SOC_{bsl,i,t})$
Data unit	t CO_2e/ha
Description	Modeled SOC stocks in the baseline scenario for sample unit *i* at time *t*, calculated by modeling SOC stock changes over the course of the preceding year
Equations	(6)
Source of data	See VMD0053
Description of measurement methods and procedures to be applied	Modeled SOC stocks in the baseline scenario are determined according to the following equation: $SOC\_soil_{bsl,i,t} = f_{SOC}(Val\ A_{bsl,i,t}, Val\ B_{bsl,i,t}, \ldots)$ Where: $SOC\_soil_{bsl,i,t}$ Modeled SOC stocks in the baseline scenario for sample unit *i* at time *t* (t CO_2e/ha) f_{SOC} Model predicting carbon dioxide emissions from the SOC pool (t CO_2e/ha) $Val\ A_{bsl,i,t}$ Value of model input variable *A* in the project scenario for sample unit *i* at time *t* (units unspecified) $Val\ B_{bsl,i,t}$ Value of model input variable *B* in the project scenario for sample unit *i* at time *t* (units unspecified) See Box 1 for sources of data and description of measurement methods and procedures to be applied to obtain values for model input variables.

Frequency of monitoring/recording	Measurements must be conducted at least every five years. Modeling as means of monitoring must be conducted prior to each verification event where verification occurs more frequently than once every five years.
QA/QC procedures to be applied	See VMD0053
Purpose of data	Calculation of baseline emissions following Quantification Approach 1
Calculation method	Not applicable
Comments	The SOC stocks at time t = 0 are calculated based on directly measured SOC content and bulk density at t = 0 or (back-) modeled to t = 0 from measurements within ±5 years of t = 0. See Section 8.2.1 for requirements for SOC content and bulk density measurements.

Data/Parameter	i
Data unit	Dimensionless
Description	Sample unit. Defined area that is selected for measurement and monitoring, such as a field or stratum. See also definition in Section 3.
Equations	(6)–(33), (40)–(50)
Source of data	Determined in project area
Description of measurement methods and procedures to be applied	The sample unit is determined prior to verification.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See definition in Section 3 for considerations on defining sample units
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	A_i
Data unit	Hectare

Description	Area of sample unit i
Equations	(7), (9), (12), (13), (15), (19), (22), (25), (28), (30), (33), (40)–(50)
Source of data	Measurement of each sample unit within the project area
Description of measurement methods and procedures to be applied	The sample unit area is measured prior to verification.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Delineation of the sample unit area may be determined using a combination of GIS coverages, ground survey data, remote imagery (satellite or aerial photographs) and other appropriate data. Any imagery or GIS datasets used must be geo-registered referencing corner points, landmarks or other intersection points.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	Other units used to determine area (e.g., acres) must be converted to hectares.

Data/Parameter	j
Data unit	Dimensionless
Description	Type of fossil fuel combusted
Equations	(7), (8)
Source of data	Determined in sample unit i
Description of measurement methods and procedures to be applied	See Box 1. Fossil fuel type is determined prior to verification.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Box 1
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable

Comments	None

Data/Parameter	$EF_{CO2,j}$
Data unit	t CO_2e/liter
Description	Emission factor for fossil fuel *j* (gasoline or diesel) combusted
Equations	(8)
Source of data	Table 3.3.1 Chapter 3 Volume 2 in IPCC (2019)
Description of measurement methods and procedures to be applied	For gasoline EF_{CO2} = 0.002810 t CO_2e per liter. For diesel EF_{CO2} = 0.002886 t CO_2e per liter
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	See “Source of data”
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	Assumes four-stroke gasoline engine for gasoline combustion and default values for energy content of 47.1 GJ/t and 45.66 GJ/t for gasoline and diesel respectively (IEA, 2004)

Data/Parameter	$FFC_{wp,j,i,t}$
Data unit	Liters
Description	Consumption of fossil fuel type *j* for sample unit *i* in year *t* in the project scenario
Equations	(8)
Source of data	See Box 1
Description of measurement methods and procedures to be applied	Fossil fuel consumption may be monitored or the amount of fossil fuel combusted may be estimated using fuel efficiency (e.g., l/100 km, l/t-km, l/hour) of the vehicle type and the appropriate unit of use for the

	selected fuel efficiency (e.g., km driven where efficiency is given in l/100 km).
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of project emissions
Calculation method	Fuel efficiency factors may be obtained from Chapter 3, Volume 2 of IPCC (2019).
Comments	For all equations, the subscript *bsl* must be substituted by *wp* to make clear that the relevant values are being quantified for the project scenario.

Data/Parameter	$EF_{Limestone}$ and $EF_{Dolomite}$
Data unit	t C/(t limestone or dolomite)
Description	Emission factor for the application of calcitic limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) (i.e., liming)
Equations	(10)
Source of data	Section 11.3, Chapter 11, Volume 4 in IPCC (2019)
Description of measurement methods and procedures to be applied	IPCC (2019) values: for calcitic limestone $EF_{Limestone}$ = 0.12 t C/t limestone, for dolomite, $EF_{Dolomite}$ = 0.13 t C/t dolomite.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	See "Source of Data" and Section 8.3 under Quantification Approach 3
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$f(CH4\_soil_{bsl,i,t})$

Data unit	t CH_4/ha
Description	Modeled methane emissions from the soil in the baseline scenario for sample unit *i* at time *t*, calculated by modeling soil methane fluxes over the course of the preceding year
Equations	(11)
Source of data	Modeled in the project area
Description of measurement methods and procedures to be applied	Modeled SOC stocks in the baseline scenario are determined according to the following equation: $f(CH4\_soil_{bsl,i,t}) = f_{CH4soil}(Var\ A_{bsl,i,t}, Var\ B_{bsl,i,t}, \ldots)$ Where: $f(CH4\_soil_{bsl,i,t})$ Modeled methane emissions from the SOC pool in the baseline scenario for sample unit *i* at time *t* (t CH_4/ha) $f_{CH4soil}$ Model predicting methane emissions from the SOC pool $Val\ A_{bsl,i,t}$ Value of model input variable *A* in the baseline scenario for sample unit *i* at time *t* (units unspecified) $Val\ B_{bsl,i,t}$ Value of model input variable B in the baseline scenario for sample unit *i* at time *t* (units unspecified) See Box 1 for sources of data and description of measurement methods and procedures to be applied to obtain values for model input variables.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See VMD0053
Purpose of data	Calculation of baseline and project emissions in Quantification Approach 1
Calculation method	Methods are specific to the model used.
Comments	None

Data/Parameter	$EF_{ent,l,P}$
Data unit	kg CH_4/(head × year)

Description	Enteric fermentation emission factor for livestock type *l* and productivity system *P*
Equations	(12)
Source of data	See Section 8.3 under Quantification Approach 3. Where no alternative information source is available that is applicable to the project conditions, project proponents may derive emission factors for each category of livestock estimated based on the gross energy intake and methane conversion factor for the category by following the guidance under "Tier 2 Approach for Methane Emissions from Enteric Fermentation" in Section 10.3.2, Chapter 10, Volume 4 of IPCC (2019). Where project proponents are able to justify a lack of sufficient activity data and project-specific information sources, Tier 1 and Tier 1a enteric fermentation emission factors from Tables 10.10 or 10.11, Chapter 10, Volume 4 in IPCC (2019) may be selected.
Description of measurement methods and procedures to be applied	When using emission factors from Tables 10.10 and 10.11 (Chapter 10, Volume 4 in IPCC, 2019), the region most applicable to the project area must be selected. The tabulations in Annex 10A.1 (IPCC, 2019) provide details of the underlying animal characteristics such as weight, growth rate and milk production used to develop the emission factors. Where project activities lead to agricultural systems transitioning from local low input productivity systems to higher productivity systems, more than one emission factor given for a specific animal category may be applied.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	See "Source of data" and Section 8.3 under Quantification Approach 3
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$Pop_{wp,l,i,t,P}$
Data unit	Head
Description	Population of grazing livestock of type *l* in the project scenario in sample unit *i* for productivity system *P* in year *t*
Equations	(12), (13), (29)

Source of data	See Box 1
Description of measurement methods and procedures to be applied	Record of number of grazing livestock by type. Information will be monitored via direct consultation with, and substantiated with a written attestation from, the farmer or landowner of the sample unit. Any quantitative information (e.g., discrete or continuous numeric variables) on ALM practices must be supported by one or more forms of documented evidence pertaining to the selected sample unit and relevant monitoring period (e.g., management logs, receipts or invoices, farm equipment specifications).
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of project emissions
Calculation method	Not applicable
Comments	For all equations, the subscript *bsl* must be substituted by *wp* to make clear that the relevant values are being quantified for the project scenario.

Data/Parameter	l
Data unit	Dimensionless
Description	Type of livestock
Equations	(12)–(14), (24), (29), (32), (34)
Source of data	Determined in sample unit i
Description of measurement methods and procedures to be applied	See Box 1. Livestock type is determined prior to verification.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See Box 1
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable

Comments	None

Data/Parameter	P
Data unit	Unitless
Description	Productivity system
Equations	(12), (28), (29)
Source of data	Subsection “Definitions of High and Low Productivity Systems,” Section 10.2, Chapter 10, Volume 4 of IPCC (2019)
Description of measurement methods and procedures to be applied	When using emission factors from IPCC (2019), project proponents must differentiate between high- and low productivity systems for each livestock species to define value from Lookup Tables 10A.1 to 10A.9. Information will be monitored via direct consultation with, and substantiated with a written attestation from, the farmer or landowner of the sample unit. See also Box 1.
Frequency of monitoring/recording	To confirm that productivity system remains the same, monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently. Any changes to the productivity system must be documented in each monitoring report.
QA/QC procedures to be applied	See “Source of data” and Section 8.3 under Quantification Approach 3
Purpose of data	Calculation of baseline and project emissions
Calculation method	Following descriptions in IPCC (2019), basic population estimates may be applied (see “Source of data”).
Comments	None

Data/Parameter	$AWMS_{l,i,t,P,S}$
Data unit	Dimensionless
Description	Fraction of total annual volatile solids for each livestock type l that is managed in manure management system S in the project area, for productivity system P
Equations	(13), (29)
Source of data	See Section 8.3 under Quantification Approach 3. Where project proponents are able to justify a lack of sufficient activity data and project-specific information sources, Tier 1 average values for animal waste management systems (manure management systems) from

	Tables 10A.6 to 10A.9, Chapter 10, Volume 4 in IPCC (2019) may be selected.
Description of measurement methods and procedures to be applied	As emissions from manure management systems are highly temperature dependent, the climate zone associated with the entire project area where manure is managed must be considered.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	See “Source of data” and Section 8.3 under Quantification Approach 3
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$EF_{CH4,md,l,P,S}$
Data unit	g CH_4/(kg volatile solids)
Description	Emission factor for methane emissions from manure deposition for livestock type *l* in productivity system *P* and manure management system *S*
Equations	(13)
Source of data	See Section 8.3 under Quantification Approach 3. Where no information source is available that is applicable to the project conditions, projects may derive emission factors based on project-specific manure characteristics and animal waste management system characteristics following the guidance under Tier 2 in Section 10.4.2, Chapter 10, Volume 4 of IPCC (2019). Where project proponents are able to justify a lack of sufficient activity data and project-specific information sources, Tier 1 and Tier 1a from Tables 10.14 and 10.15, Chapter 10, Volume 4 in IPCC (2019) may be selected.
Description of measurement methods and procedures to be applied	See “Source of data”
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project

	conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	See “Source of data” and Section 8.3 under Quantification Approach 3
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	S
Data unit	Unitless
Description	Manure management system
Equations	(13), (23), (24), (28), (29)
Source of data	Table 10.18, Chapter 10, Volume 4 in IPCC (2019)
Description of measurement methods and procedures to be applied	See Section 8.3 under Quantification Approach 3. When using methane and nitrous oxide emission factors from IPCC (2019), project proponents must differentiate between manure management systems to define value from Lookup Tables 10.14 and 10.17. The referenced table of IPCC (2019) provides Tier 1a emission factors, which consider different aeration and mixing regimes as well as other factors such as water content, thus influencing CH_4 and N_2O emissions differently.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	See “Source of data” and Section 8.3 under Quantification Approach 3
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$VS_{rate,l,P}$
Data unit	kg volatile solids/(1000 kg animal mass × day)
Description	Default volatile solids excretion rate for livestock type l and productivity system P

Equations	(14)
Source of data	See Section 8.3 under Quantification Approach 3. Where no information source is available that is applicable to the project conditions, projects may derive default factors using Equation 10.24 in Chapter 10, Volume 4 in IPCC (2019). Where project proponents are able to justify a lack of sufficient activity data and project-specific information sources, Tier 1 and Tier 1a from Table 10.13a, Chapter 10, Volume 4 in IPCC (2019) may be selected.
Description of measurement methods and procedures to be applied	The volatile solids excretion rate is determined based on livestock type. Where agricultural systems are differentiated into low and high productivity systems in Table 10.13a in Chapter 10, Volume 4 in IPCC (2019), the mean value may be selected.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	See “Source of data” and Section 8.3 under Quantification Approach 3
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$W_{wp,l,i,t,P}$
Data unit	kg animal mass/head
Description	Average weight in the project scenario of livestock type *l* for sample unit *i* in productivity system *P* in year *t*
Equations	(14)
Source of data	Estimation based on management records from project area.
Description of measurement methods and procedures to be applied	Information will be monitored via direct consultation with, and substantiated with a written attestation from, the farmer or landowner of the sample unit. Any quantitative information (e.g., discrete or continuous numeric variables) on ALM practices must be supported by one or more forms of documented evidence pertaining to the selected sample unit and relevant monitoring period (e.g., management logs, receipts or invoices, farm equipment specifications).

Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of project emissions
Calculation method	Not applicable
Comments	For all equations, the subscript *bsl* must be substituted by *wp* to make clear that the relevant values are being quantified for the project scenario.

Data/Parameter	CF_c
Data unit	Proportion of pre-fire fuel biomass consumed
Description	Combustion factor for agricultural residue type *c*
Equations	(15), (33)
Source of data	Table 2.6, Chapter 2, Volume 4 in IPCC (2019)
Description of measurement methods and procedures to be applied	The combustion factor is selected based on the agricultural residue type burned.
Frequency of monitoring/recording	Source of data for combustion factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC, 2003 Section 5.5 or IPCC, 2000 Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$EF_{c,CH4}$
Data unit	g CH_4/kg dry matter burnt

Description	Methane emission factor for the burning of agricultural residue type *c*
Equations	(15)
Source of data	Table 2.5, Chapter 2, Volume 4 in IPCC (2019)
Description of measurement methods and procedures to be applied	The emission factor is selected based on the agricultural residue type burned.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC, 2003 Section 5.5 or IPCC, 2000 Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	c
Data unit	Dimensionless
Description	Type of agricultural residue
Equations	(15), (33)
Source of data	Determined in sample unit *i*
Description of measurement methods and procedures to be applied	See Box 1. Agricultural residue type is determined prior to verification.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC, 2003 Section 5.5 or IPCC, 2000 Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable

Comments	None

Data/Parameter	$MB_{wp,c,i,t}$
Data unit	kg
Description	Mass of agricultural residues of type *c* burned in the project for sample unit *i* in year *t*
Equations	(15), (33)
Source of data	See Box 1
Description of measurement methods and procedures to be applied	Estimate the aboveground biomass of grassland before burning for at least three plots (1 m × 1 m). The difference in the aboveground biomass is the aboveground biomass burnt.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of project emissions
Calculation method	Not applicable
Comments	For all equations, the subscript *bsl* must be substituted by *wp* to make clear that the relevant values are being quantified for the project scenario.

Data/Parameter	$f(N2O\_soil_{bsl,i,t})$
Data unit	t N_2O/ha
Description	Modeled nitrous oxide emissions from soil in the baseline scenario for sample unit *i* in year *t*, calculated by modeling soil fluxes of nitrogen forms over the course of the preceding year
Equations	(16)
Source of data	Modeled in the project area

Description of measurement methods and procedures to be applied	Modeled nitrous oxide emissions from soil in the baseline scenario are determined according to the following equation: $$f(N2O\_soil_{bsl,i,t}) = f_{N2Osoil}(Var\ A_{bsl,i,t}, Var\ B_{bsl,i,t}, \dots)$$ Where: $f(N2O\_soil_{bsl,i,t})$ Modeled nitrous oxide emissions from soil in the baseline scenario for sample unit *i* in year *t*, calculated by modeling soil fluxes of nitrogen forms over the course of the preceding year (t N_2O/ha) $f_{N2Osoil}$ Model predicting nitrous oxide emissions from the SOC pool $Val\ A_{bsl,i,t}$ Value of model input variable *A* in the baseline scenario for sample unit *i* at time *t* (units unspecified) $Val\ B_{bsl,i,t}$ Value of model input variable *B* in the baseline scenario for sample unit *i* at time *t* (units unspecified) See Box 1 for sources of data and description of measurement methods and procedures to be applied to obtain values for model input variables.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See VMD0053
Purpose of data	Calculation of baseline and project emissions in Quantification Approach 1
Calculation method	Not applicable
Comments	None

Data/Parameter	$EF_{Ndirect}$
Data unit	t N_2O-N/t N applied
Description	Emission factor for direct nitrous oxide emissions from N additions from synthetic fertilizers, organic amendments and crop residues
Equations	(19), (25)
Source of data	See Section 8.3 under Quantification Approach 3. Where no information source is available that is applicable to the project conditions, project proponents may derive emission factors following the guidance in Chapter 11 Section 11.2.1.1 and Chapter 2 Section 2.2.4 in IPCC (2019). The emission factors will depend on, for example, SOC content, soil texture, drainage, soil pH, N application rate per

	fertilizer type, fertilizer type, liquid or solid form of organic fertilizer, irrigation and type of crop with differences between legumes, non-leguminous arable crops and grass. Where project proponents are able to justify a lack of sufficient activity data and project-specific information sources, an appropriate disaggregated Tier 1 value from Table 11.1, Chapter 11, Volume 4 in IPCC (2019) may be selected.
Description of measurement methods and procedures to be applied	See "Source of data"
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC, 2003 Section 5.5 or IPCC, 2000 Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	The emission factor is applicable to N additions from mineral fertilizers, organic amendments and crop residues, and N mineralized from mineral soil as a result of loss of SOC. Wet climates occur in temperate and boreal zones where the ratio of annual precipitation to potential evapotranspiration is greater than 1, and in tropical zones where annual precipitation is greater than 1000 mm. Dry climates occur in temperate and boreal zones where the ratio of annual precipitation to potential evapotranspiration is less than 1, and in tropical zones where annual precipitation is less than 1000 mm.

Data/Parameter	NC_{SF}
Data unit	t N/t fertilizer
Description	N content of synthetic fertilizer type *SF*
Equations	(20)
Source of data	See Box 1
Description of measurement methods	N content is determined following fertilizer manufacturer's specifications.

and procedures to be applied	
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently. Parameter value must be updated when synthetic fertilizer product is changed or when new manufacturer's specifications are issued.
QA/QC procedures to be applied	See "Source of data" and Section 8.3 under Quantification Approach 3
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	SF
Data unit	Dimensionless
Description	Type of synthetic N fertilizer
Equations	(20)
Source of data	Determined in sample unit i
Description of measurement methods and procedures to be applied	See Box 1. Synthetic fertilizer type is determined prior to verification.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$M_{wp,SF,i,t}$
Data unit	t fertilizer

Description	Mass of N-containing synthetic fertilizer type *SF* applied in the project for sample unit *i* in year *t*
Equations	(20)
Source of data	Management records from project area
Description of measurement methods and procedures to be applied	Information will be monitored via direct consultation with, and substantiated with a written attestation from, the farmer or landowner of the sample unit. Any quantitative information (e.g., discrete or continuous numeric variables) on ALM practices must be supported by one or more forms of documented evidence pertaining to the selected sample unit and relevant monitoring period (e.g., management logs, receipts or invoices, farm equipment specifications).
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of project emissions
Calculation method	Not applicable
Comments	For all equations, the subscript *bsl* must be substituted by *wp* to make clear that the relevant values are being quantified for the project scenario.

Data/Parameter	NC_{OF}
Data unit	t N/t fertilizer
Description	N content of organic fertilizer type *OF*
Equations	(21)
Source of data	Peer-reviewed published data may be used. For example, default manure N content may be selected from Edmonds et al. (2003) cited in US EPA (2011) or other regionally appropriate sources such as the European Environment Agency.
Description of measurement methods and procedures to be applied	See “Source of data”
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently. Parameter value must be updated when organic fertilizer product is changed or as new default values become available in peer-reviewed publications or databases.

QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	OF
Data unit	Dimensionless
Description	Type of organic N fertilizer
Equations	(21)
Source of data	Determined in sample unit *i*
Description of measurement methods and procedures to be applied	See Box 1. Organic fertilizer type is determined prior to verification.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$M_{wp,OF,i,t}$
Data unit	t fertilizer
Description	Mass of N-containing organic fertilizer type *OF* applied in the project for sample unit *i* in year *t*
Equations	(21)
Source of data	Management records from project area

Description of measurement methods and procedures to be applied	Information will be monitored via direct consultation with, and substantiated with a written attestation from, the farmer or landowner of the sample unit. Any quantitative information (e.g., discrete or continuous numeric variables) on ALM practices must be supported by one or more forms of documented evidence pertaining to the selected sample unit and relevant monitoring period (e.g., management logs, receipts or invoices, farm equipment specifications).
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of project emissions
Calculation method	Not applicable
Comments	For all equations, the subscript *bsl* must be substituted by *wp* to make clear that the relevant values are being quantified for the project scenario.

Data/Parameter	$Frac_{GASF,l,S}$
Data unit	Dimensionless
Description	Fraction of all synthetic N added to soils that volatilizes as NH_3 and NO_x for livestock type l and manure management system S
Equations	(23)
Source of data	See Section 8.3 under Quantification Approach 3. When no information source is available that is applicable to the project conditions, project proponents may define value from Lookup Table 10.22, Chapter 10, Volume 4 in IPCC (2019).
Description of measurement methods and procedures to be applied	See “Source of data”
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC, 2003 Section 5.5 or IPCC, 2000 Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions

Calculation method	Not applicable
Comments	None

Data/Parameter	$Frac_{GASM,l,S}$
Data unit	Dimensionless
Description	Fraction of all organic N added to soils and N in manure and urine deposited on soils that volatilizes as NH_3 and NO_x for livestock type *l* and manure management system *S*
Equations	(23), (31)
Source of data	See Section 8.3 under Quantification Approach 3. When no information source is available that is applicable to the project conditions, project proponents may define value from Lookup Table 10.22, Chapter 10, Volume 4 in IPCC (2019).
Description of measurement methods and procedures to be applied	See "Source of data"
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC, 2003 Section 5.5 or IPCC, 2000 Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$Frac_{LEACH,l,S}$
Data unit	Dimensionless
Description	Fraction of N (synthetic or organic) added to soils and N in manure and urine deposited on soils that is lost through leaching and runoff, in regions where leaching and runoff occurs
Equations	(24), (32)

Source of data	See Section 8.3 under Quantification Approach 3. When no information source is available that is applicable to the project conditions, project proponents may define value from Lookup Table 11.3, Chapter 11, Volume 4 in IPCC (2019).
Description of measurement methods and procedures to be applied	When using values from IPCC (2019), for wet climates and for dry climate regions where irrigation (other than drip irrigation) is used, a value of 0.24 is applied. For all other dry climate regions, a value of zero is applied.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC, 2003 Section 5.5 or IPCC, 2000 Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	Wet climates occur in temperate and boreal zones where the ratio of annual precipitation to potential evapotranspiration is greater than 1, and in tropical zones where annual precipitation is greater than 1000 mm. Dry climates occur in temperate and boreal zones where the ratio of annual precipitation to potential evapotranspiration is less than 1, and in tropical zones where annual precipitation is less than 1000 mm.

Data/Parameter	EF_{Nleach}
Data unit	t N_2O-N/t N leached and runoff
Description	Emission factor for nitrous oxide emissions from leaching and runoff
Equations	(24), (32)
Source of data	See Section 8.3 under Quantification Approach 3. When no information source is available that is applicable to the project conditions, project proponents may define value from Lookup Table 11.3, Chapter 11, Volume 4 in IPCC (2019).
Description of measurement methods and procedures to be applied	See “Source of data”
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the

	project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
<	None

Data/Parameter	$MB_{g,wp,i,t}$
Data unit	t dm
Description	Annual aboveground and belowground dry matter of N-fixing species *g* returned to soils for sample unit *i* in year *t*
Equations	(26)
Source of data	Aboveground and belowground dry matter in N-fixing species *g* returned to soil may be directly measured or peer-reviewed published data may be used.
Description of measurement methods and procedures to be applied	Information will be monitored via direct consultation with, and substantiated with a written attestation from, the farmer or landowner of the sample unit. Any quantitative information (e.g., discrete or continuous numeric variables) on ALM practices must be supported by one or more forms of documented evidence pertaining to the selected sample unit and relevant monitoring period (e.g., management logs, receipts or invoices, farm equipment specifications).
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of project emissions
Calculation method	Not applicable
Comments	For all equations, the subscript *bsl* must be substituted by *wp* to make clear that the relevant values are being quantified for the project scenario.

Data/Parameter	$N_{content,g}$

Data unit	t N/t dm
Description	Fraction of N in dry matter for N-fixing species *g*
Equations	(26)
Source of data	See Section 8.3 under Quantification Approach 3. When no information source is available that is applicable to the project conditions, project proponents may define value from Lookup Table 11.2, Chapter 11, Volume 4 in IPCC (2019).
Description of measurement methods and procedures to be applied	The fraction of N in dry matter is determined based on the N-fixing species type.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	*g*
Data unit	Dimensionless
Description	Type of N-fixing species
Equations	(26)
Source of data	Determined in sample unit *i*
Description of measurement methods and procedures to be applied	See Box 1. N-fixing species type is determined prior to verification.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.

Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$EF_{N2O,md,l,S}$
Data unit	kg N_2O-N/kg N input
Description	Emission factor for nitrous oxide from manure and urine deposited on soils by livestock type *l* and manure management system *S*
Equations	(28)
Source of data	See Section 8.3 under Quantification Approach 3. Where project proponents are able to justify a lack of sufficient activity data and project-specific information sources, Tier 1 and Tier 1a from Table 10.21, Chapter 10, Volume 4 in IPCC (2019) may be selected.
Description of measurement methods and procedures to be applied	See “Source of data”
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$Nex_{l,P}$
Data unit	kg N deposited/(head × year)
Description	Annual average nitrogen excretion per head of livestock type *l* in productivity system *P*
Equations	(29)

Source of data	See Section 8.3 under Quantification Approach 3. Where no alternative information source is available that is applicable to the project conditions, project proponents may derive default factors using Equations 10.31 or 10.31a in Chapter 10, Volume 4 in IPCC (2019). Where project proponents are able to justify a lack of sufficient activity data and project-specific information sources, Tier 1 and Tier 1a from Table 10.19, Chapter 10, Volume 4 in IPCC (2019) may be selected.
Description of measurement methods and procedures to be applied	See “Source of data”
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	EF_{Nvolat}
Data unit	t N_2O-N/(t NH_3-N + NO_x-N volatilized)
Description	Emission factor for nitrous oxide emissions from atmospheric deposition of N on soils and water surfaces
Equations	(23), (31)
Source of data	See Section 8.3 under Quantification Approach 3. When no information source is available that is applicable to the project conditions, project proponents may define value from Lookup Table 11.3, Chapter 11, Volume 4 in IPCC (2019).
Description of measurement methods and procedures to be applied	See “Source of data”
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.

QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$EF_{c,N2O}$
Data unit	g N_2O/kg dry matter burnt
Description	Nitrous oxide emission factor for the burning of agricultural residue type *c*
Equations	(33)
Source of data	See Section 8.3 under Quantification Approach 3. When no information source is available that is applicable to the project conditions, project proponents may define value from Lookup Table 2.5, Chapter 2, Volume 4 in IPCC (2019)
Description of measurement methods and procedures to be applied	The emission factor is selected based on the agricultural residue type.
Frequency of monitoring/recording	Source of data for emission factor must be monitored every five years and must be updated when more accurate data applicable to the project conditions becomes available following the guidance in Section 8.3 under Quantification Approach 3.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$M\_OA_{wp,l,t}$
Data unit	tonnes
Description	Mass of organic amendment applied as fertilizer on the project area in year *t*

Equations	(34)
Source of data	Management records from project area
Description of measurement methods and procedures to be applied	For manure application, data should be disaggregated for each livestock type *l*
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of leakage from application of new organic amendments from outside of the project area
Calculation method	Not applicable
Comments	None

Data/Parameter	$CC_{wp,l,t}$
Data unit	t C/t manure
Description	Carbon content of manure from livestock type *l* applied as fertilizer on the project area in year *t*
Equations	(34)
Source of data	See Box 1
Description of measurement methods and procedures to be applied	Record of carbon content of manure
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Calculation of project emissions from leakage
Calculation method	Not applicable
Comments	None

Data/Parameter	$P_{wp,p}$
Data unit	Output (e.g., kg)/ha
Description	Average productivity for product *p* during the project period
Equations	(35), (36)
Source of data	Farm productivity (e.g., yield) records
Description of measurement methods and procedures to be applied	Measured using locally available technologies (e.g., mobile weighing devices, commercial scales, storage volume measurements, fixed scales, weigh scale tickets)
Frequency of monitoring/recording	Each growing season
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Determination of project productivity for market leakage analysis
Calculation method	Not applicable
Comments	None

Data/Parameter	p
Data unit	Categorical variable
Description	Crop/livestock product
Equations	(35), (36)
Source of data	See Box 1
Description of measurement methods and procedures to be applied	Not applicable
Frequency of monitoring/recording	Each growing season
QA/QC procedures to be applied	See Box 1
Purpose of data	Identification of crop/livestock product for market leakage analysis

Calculation method	Not applicable
Comments	None

Data/Parameter	$RP_{wp,p}$
Data unit	Output (e.g., kg)/ha
Description	Average regional productivity for product *p* during the project period
Equations	(36)
Source of data	Regional productivity data from government (e.g., USDA Actual Production History data), industry, published, academic or international organization (e.g., FAO) sources
Description of measurement methods and procedures to be applied	Not applicable
Frequency of monitoring/recording	Every 10 years
QA/QC procedures to be applied	Guidance provided in IPCC (2003) Section 5.5 or IPCC (2000) Chapter 8 must be applied.
Purpose of data	Determination of project productivity ratio for market leakage analysis
Calculation method	Not applicable
Comments	None

Data/Parameter	$\overline{SOC_{bsl,i,t}}$
Data unit	t CO_2e/ha
Description	Areal mean SOC stocks in the baseline scenario for sample unit *i* in year *t*
Equations	(40)
Source of data	Modeled in the project area or measured in baseline control sites
Description of measurement methods and procedures to be applied	See parameter table for $f(SOC_{bsl,i,t})$ for modeled SOC stocks under Quantification Approach 1.

	Measured SOC under Quantification Approach 2 must be determined from samples collected from sample plots located within each baseline control site. See Section 8.2.1 for requirements for SOC content and bulk density measurements.
Frequency of monitoring/recording	Measurements must be conducted at least every five years. Modeling as means of monitoring must be conducted prior to each verification event where verification occurs more frequently than once every five years. SOC stocks in the baseline scenario for sample unit *i* must be reported every five years or more frequently.
QA/QC procedures to be applied	See Section 8.2.1 and, for Quantification Approach 1, VMD0053
Purpose of data	Calculation of baseline emissions
Calculation method	Not applicable
Comments	SOC stocks at time *t* = 0 are calculated based on directly measured SOC content and bulk density at *t* = 0 or (back-) modeled to *t* = 0 from measurements collected within ±5 years of *t* = 0. This initially measured SOC is the same in both the baseline and project scenarios at the outset of the project (i.e., $SOC_{wp,i,0} = SOC_{bsl,i,0}$) in Quantification Approach 1.

Data/Parameter	$\overline{SOC}_{bsl,i,t-1}$
Data unit	t CO_2e/ha
Description	Areal mean SOC stocks in the baseline scenario for sample unit *i* in year *t* − 1
Equations	(40)
Source of data	Modeled in the project area or measured in baseline control sites
Description of measurement methods and procedures to be applied	See parameter table for $\overline{SOC}_{bsl,i,t}$
Frequency of monitoring/recording	Measurements must be conducted at least every five years. Modeling as means of monitoring must be conducted prior to each verification event where verification occurs more frequently than once every five years. SOC stocks in the baseline scenario for sample unit *i* must be reported every five years or more frequently.

QA/QC procedures to be applied	See Section 8.2.1 and, for Quantification Approach 1, VMD0053
Purpose of data	Calculation of baseline emissions
Calculation method	Not applicable
Comments	See parameter table for $\overline{SOC_{bsl,i,t}}$ See Section 8.2.1 for requirements for SOC content and bulk density measurements

Data/Parameter	$\overline{SOC_{wp,i,t}}$
Data unit	t CO_2e/ha
Description	Areal mean SOC stocks in the project scenario for sample unit *i* in year *t*
Equations	(40)
Source of data	Modeled or measured in the project area
Description of measurement methods and procedures to be applied	Modeled SOC stocks in the project scenario are determined following the guidance in VMD0053 and according to the following equation: $f(SOC_{wp,i,t}) = f_{SOC}(Var\ A_{wp,i,t}, Var\ B_{wp,i,t}, \ldots)$ Where: $f(SOC_{wp,i,t})$ = Modeled carbon dioxide emissions from SOC pool in the project for sample unit *i* at time *t* (t CO_2e/ha) f_{SOC} = Model predicting carbon dioxide emissions from the SOC pool (t CO_2e/ha) $Val\ A_{wp,i,t}$ = Value of model input variable *A* in the project scenario for sample unit *i* at time *t* (units unspecified) $Val\ B_{wp,i,t}$ = Value of model input variable *B* in the project scenario for sample unit *i* at time *t* (units unspecified) See Box 1 for sources of data and description of measurement methods and procedures to be applied to obtain values for model input variables.
Frequency of monitoring/recording	Measurements must be conducted at least every five years. Modeling as means of monitoring must be conducted prior to each verification event where verification occurs more frequently than once every five years.
QA/QC procedures to be applied	See Section 8.2.1 and for Quantification Approach 1, VMD0053
Purpose of data	Calculation of project emissions
Calculation method	Not applicable

Comments	Initially measured SOC stocks are the same in both the baseline and project scenarios at the outset of the project (i.e., $SOC_{wp,i,0} = SOC_{bsl,i,0}$) under Quantification Approach 1. SOC stocks at time $t = 0$ are calculated based on directly measured SOC content and bulk density at $t = 0$ or (back-) modeled to $t = 0$ from measurements collected within ±5 years of $t = 0$. SOC stocks in the project scenario for sample unit i must be reported every five years or more frequently under Quantification Approaches 1 and 2.

Data/Parameter	$\overline{SOC_{wp,i,t-1}}$
Data unit	t CO_2e/ha
Description	Areal mean SOC stocks in the project scenario for sample unit i in year $t-1$
Equations	(40)
Source of data	Modeled or measured in the project area
Description of measurement methods and procedures to be applied	See parameter table for $\overline{SOC_{wp,i,t}}$
Frequency of monitoring/recording	Measurements must be conducted at least every five years. Modeling as means of monitoring must be conducted prior to each verification event where verification occurs more frequently than once every five years.
QA/QC procedures to be applied	See parameter table for $\overline{SOC_{wp,i,t}}$
Purpose of data	Calculation of project emissions
Calculation method	Not applicable
Comments	See parameter table for $\overline{SOC_{wp,i,t}}$

Data/Parameter	$\overline{\Delta C_{TREE,bsl,i,t}}$
Data unit	t CO_2e/ha
Description	Areal mean change in carbon stocks in trees in the baseline
Equations	Section 8.2.2 and (42)

Source of data	Determined in project area
Description of measurement methods and procedures to be applied	Calculated using the CDM A/R tools *Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities* and *Simplified baseline and monitoring methodology for small scale CDM afforestation and reforestation project activities implemented on lands other than wetlands*
Frequency of monitoring/recording	Monitoring must be conducted at least every five years or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See "Description of measurement methods and procedures to be applied"
Purpose of data	Calculation of baseline emissions
Calculation method	See "Description of measurement methods and procedures to be applied"
Comments	None

Data/Parameter	$\overline{\Delta C_{SHRUB,bsl,i,t}}$
Data unit	t CO_2e/ha
Description	Areal mean change in carbon stocks in shrubs in the baseline
Equations	Section 8.2.2 and (43)
Source of data	Determined in project area
Description of measurement methods and procedures to be applied	Calculated using the CDM A/R tools *Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities* and *Simplified baseline and monitoring methodology for small scale CDM afforestation and reforestation project activities implemented on lands other than wetlands*
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See "Description of measurement methods and procedures to be applied"
Purpose of data	Calculation of baseline emissions
Calculation method	See "Description of measurement methods and procedures to be applied"
Comments	None

Data/Parameter	$\overline{\Delta C_{TREE,wp,i,t}}$
Data unit	t CO_2e/ha
Description	Areal mean change in carbon stocks in trees in the project
Equations	Section 8.2.2 and (42)
Source of data	Determined in project area
Description of measurement methods and procedures to be applied	Calculated using the CDM A/R tools *Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities* and *Simplified baseline and monitoring methodology for small scale CDM afforestation and reforestation project activities implemented on lands other than wetlands*. Where woody biomass is harvested, projects must calculate the long-term average GHG benefit following guidance in the latest version of the VCS Methodology Requirements and of the VCS Standard.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See "Description of measurement methods and procedures to be applied"
Purpose of data	Calculation of project emissions
Calculation method	See "Description of measurement methods and procedures to be applied"
Comments	None

Data/Parameter	$\overline{\Delta C_{SHRUB,wp,i,t}}$
Data unit	t CO_2e/ha
Description	Areal mean change in carbon stocks in shrubs in the project
Equations	Section 8.2.2 and (43)
Source of data	Determined in project area
Description of measurement methods and procedures to be applied	Calculated using the CDM A/R tools *Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities* and *Simplified baseline and monitoring methodology for small scale CDM afforestation and reforestation project activities implemented on lands other than wetlands*. Where woody biomass is harvested, projects must calculate the long-term average GHG benefit

	following guidance in the latest version of the VCS Methodology Requirements and of the VCS Standard.
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	See “Description of measurement methods and procedures to be applied”
Purpose of data	Calculation of project emissions
Calculation method	See “Description of measurement methods and procedures to be applied”
Comments	None

Data/Parameter	$\bullet$
Data unit	Dimensionless
Description	Gas or pool
Equations	(51)–(54), (57), (65)
Source of data	Determined in sample unit *i*
Description of measurement methods and procedures to be applied	Not applicable
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Not applicable
Purpose of data	Calculation of baseline and project emissions
Calculation method	Not applicable
Comments	None

Data/Parameter	$\bar{\Delta}_{\bullet,t}$ and $\bar{\bullet}_t$
Data unit	t CO_2e/ha
Description	Mean emission reductions from pool or source $\bullet$, or stock of pool $\bullet$, in year *t*

Equations	(53), (54), (65)
Source of data	Calculated from modeled or calculated values in the project area
Description of measurement methods and procedures to be applied	Not applicable
Frequency of monitoring/recording	Calculations and recording must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	Comparison of project results with values from peer-reviewed literature under similar conditions. Raw data from laboratory analysis as well as calculation spreadsheets and/or computer code used for calculations must be provided as requested by the VVB.
Purpose of data	Calculation of emission reductions
Calculation method	The mean emission reductions from pool or source •, or stock of pool •, at time *t* are estimated using unbiased statistical approaches, such as from Cochran (1977). Application of this methodology may employ sample units of unequal sizes, which would necessitate proper weighting of samples in deriving means.
Comments	None

Data/Parameter	$Buffer_t$
Data unit	t CO_2e
Description	Number of buffer credits to be contributed to the AFOLU pooled buffer account in year *t*
Equations	(66)
Source of data	The number of buffer credits to be contributed to the AFOLU pooled buffer account must be determined by applying the latest version of the VCS *AFOLU Non-Permanence Risk Tool*.
Description of measurement methods and procedures to be applied	Not applicable
Frequency of monitoring/recording	Monitoring must be conducted at least every five years, or prior to each verification event where verification occurs more frequently.
QA/QC procedures to be applied	The number of buffer credits to be contributed to the AFOLU pooled buffer account must be determined by applying the latest version of the VCS *AFOLU Non-Permanence Risk Tool*.

Purpose of data	Calculation of project emissions
Calculation method	The number of buffer credits to be contributed to the AFOLU pooled buffer account must be determined by applying the latest version of the VCS *AFOLU Non-Permanence Risk Tool*.
Comments	None

9.3 Description of the Monitoring Plan

The main objective of monitoring is to quantify stock change of SOC and emissions of CO_2, CH_4 and N_2O resulting from the project scenario during the verification period.

Project proponents must detail the procedures for collecting and reporting all data and parameters listed in Section 9.2. The monitoring plan must contain at least the following information:

- Description of each monitoring task to be undertaken, and the technical requirements therein;
- Definition of the accounting boundary, spatially delineating any differences in the accounting boundaries and/or quantification approaches;
- Parameters to be measured, including any parameters required for the selected model (additional to those specified in this methodology);
- Data to be collected and data collection techniques and sample designs for directly sampled parameters;
- Baseline control site management plans, where applicable, including location, boundaries and demonstration of similarity criteria (see Table 7) for each baseline control site, with adequate detail to permit implementation of the annual schedule of activities for the linked sample unit(s);
- Ten-year baseline re-evaluation plan, detailing source of regional (sub-national) agricultural production data and procedures to revise the baseline schedule of activities;
- Quality assurance and quality control (QA/QC) procedures to ensure accurate data collection; screen for, and where necessary, correct anomalous values; ensure completeness; perform independent checks on analysis results and other safeguards as appropriate;
- Data archiving procedures, including procedures for any anticipated updates to electronic file formats. All data collected as a part of monitoring, including QA/QC data, must be archived electronically and kept for at least two years after the end of the last project crediting period;
- Roles, responsibilities and capacity of monitoring team and management; and

- Modeling plan, where Quantification Approach 1 is applied. The project modeling plan must describe the model(s) selected, describe the datasets that will be used for model validation and calibration, including their sources, and specify the baseline schedule of ALM activities for each sample unit (fixed ex ante).

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APPENDIX 1: NON-EXHAUSTIVE LIST OF POTENTIAL IMPROVED ALM PRACTICES THAT COULD CONSTITUTE THE PROJECT ACTIVITY

The following list presents the main categories of practices expected to enhance SOC stocks and/or reduce GHG emissions from soils under a range of cropping and livestock systems. However, the list is non-exhaustive; there are many other improved ALM practices with the potential to enhance SOC stocks and/or reduce GHG emissions as well as emerging practices (e.g., soil inoculants). Furthermore, the terms used to denote the same or similar practices may differ regionally. Therefore, for the purposes of demonstrating eligibility (i.e., Applicability Condition 1) as well as additionality (i.e., Step 3 Common Practice) the project proponent must demonstrate that the implementation of a proposed practice constitutes an improvement over the pre-existing practice within the specific cropping and/or livestock system in the project region.

Improve fertilizer (organic or inorganic) application

- Optimization of fertilizer application (e.g., 4R Nutrient Stewardship – right source, rate, time and placement)
- Organic fertilizer application (e.g., manure, compost)
- Enhanced efficiency nitrogen fertilizers (e.g., urease/nitrification inhibitors, controlled release fertilizers)

Improve water management/irrigation

- Alteration of irrigation (e.g., precision irrigation)
- Alternate wetting and drying (AWD) in rice systems
- Groundwater level management (e.g., adjust groundwater levels to reduce peat oxidation)

Reduce tillage/improve residue management

- Reduced tillage/conservation tillage
- Strip-till/mulch-till
- No-till
- Crop residue retention
- Avoidance of residue burning

Improve crop planting and harvesting

- Rotational commercial crop
- Continuous commercial crop with cover crop

- Rotational commercial crop with cover crop
- Double cropping
- Relay cropping
- Intercropping of cover crop with commercial crop during the same growing season
- Incorporation of fungal/microbial inoculants or other soil probiotics
- Agroforestry (integration of woody species into crops)

Improve grazing management

- Rotational grazing (also known as cell and holistic grazing)
- Adaptive multi-paddock grazing (rotational, livestock numbers are adjusted to match available forage as conditions change)
- Multi-species grazing
- Grazing of cover crops and agricultural residues post-harvest
- Silvipasture (integration of woody species into pastures)
- Integrated crop-livestock system (ICLS)

APPENDIX 2: PROCEDURE TO DEMONSTRATE DEGRADATION OF PROJECT LANDS IN THE BASELINE SCENARIO

According to the IPCC, up to one quarter of the Earth's ice-free lands are affected by land degradation[47] caused by direct or indirect human-induced processes. This equates to hundreds of millions of hectares of degraded crop- and grasslands with reduced productive capacity, which adversely affects livelihoods, ecosystems and the ability to meet humanity's growing needs.

Degraded lands may be restored and rehabilitated through implementation of sustainable land management strategies, thereby reversing degradation and restoring productivity. In addition, such strategies may reduce conversion pressure on native ecosystems, generate new income opportunities and provide ecosystem services such as erosion control, regulation of groundwater recharge and enhanced above- and belowground biodiversity and carbon stocks.

Given the multiple benefits of restoration, this methodology seeks to incentivize restoration of degraded crop- and grasslands by making an exception to the land use change applicability condition that otherwise requires project lands to remain cropland or grassland throughout the project crediting period. This exception allows for a one-time conversion from grassland to cropland or vice versa. However, projects must credibly demonstrate:

1) Current and future degradation of lands in the baseline scenario, and
2) Expected improvements in soil health and associated socioenvironmental outcomes through the introduction of improved practices involving land use change.

Step 1: Demonstration of Land Degradation

The project proponent must use the CDM *Tool for the identification of degraded or degrading lands for consideration in implementing CDM A/R project activities* to demonstrate that the land is degraded at the start of the project and will continue to degrade in the baseline scenario. The tool uses a two-stage process that involves:

- Identification of project lands classified as degraded under any verifiable local, regional, national or international land classification system or credible study produced within the last 10 years; or

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[47] Olsson, L., et al. (2019). Land degradation. In P. R. Shukla et al. (Eds.). *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (pp. 345–436). Available at: https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/07_Chapter-4.pdf

- In the absence of such study, identification through direct evidence based on indicators of degradation or through comparative studies. Exact procedures are outlined in the tool.

Step 2: Demonstration of Expected Improvements Resulting from Project Implementation

The project proponent must provide an analysis of how the proposed project activities will lead to restoration of project lands. Such analysis must be based on the degradation indicators identified in Step 1 and must at minimum include expected impacts on soil health, plant (i.e., crops, forage) productivity, biodiversity, local ecosystems and livelihoods. Evidence types may include local expert analysis and relevant local, regional or national studies. Where those are not available, international studies conducted under similar biophysical and climatic conditions and with comparable management practices may be used. Evidence may include quantification of recognized indicators of degradation by direct measurement, proximal or remote sensing and/or modeling. Any experts consulted as part of the analysis should have at least 10 years of relevant experience in the project region and professional credentials (e.g., research scientist, certified agronomist).

APPENDIX 3: RECOMMENDED PROCESS FOR ASSESSING WHETHER NEW PROJECT ACTIVITY INSTANCES ARE COMMON PRACTICE

The *VCS Standard* sets out the eligibility criteria that grouped projects must develop and include in their project description. These eligibility criteria are a set of project-specific criteria that serve as a screen to determine whether any new project activity instances meet the baseline scenario and have characteristics with respect to additionality that are consistent with the initial project activity instances. The addition of new instances does not impact the additionality of the instances already included in the project.

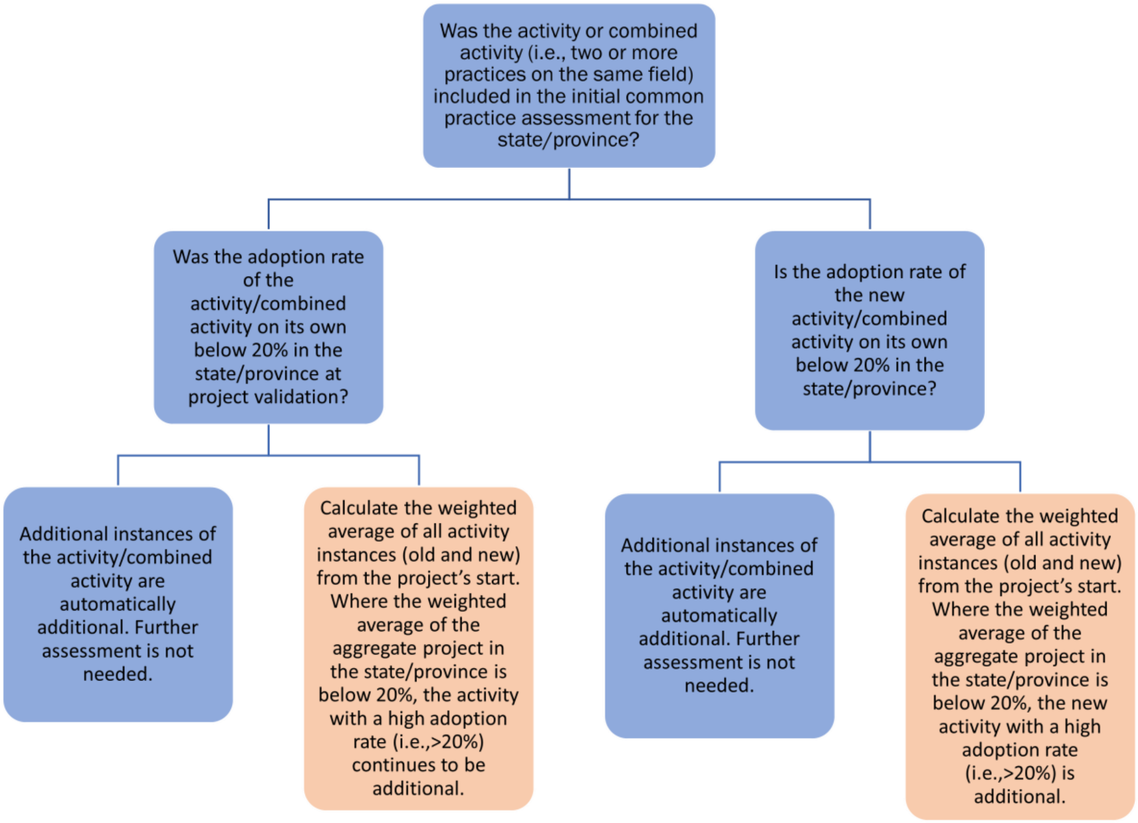
Figure 5 outlines a recommended approach for assessing common practice of new project activity instances and identifies when a new weighted average must be calculated (see Section 7 for further details). New instances with practice adoption rates below 20 percent on their own (i.e., as single or combined (two or more) activities) in the applicable stratum at validation are automatically deemed additional. New instances of any individual activity or combined activity that were not included in the initial assessment of additionality but with a current adoption rate below 20 percent are also deemed additional.

Where the project proponent seeks to add new activities or combined activities that are non-additional on their own (i.e., with single or combined adoption rates currently greater than 20 percent) in a given stratum, a new weighted average should be calculated (see Step 3 of Section 7). To calculate the weighted average, project proponents should use the total area across the entire project currently under each ALM activity (i.e., old and new activity instances). On fields where new project activities have been added to existing project activities since the last monitoring period, the combined activity adoption rate should be used. For example, where an area of land entered the project at the outset by adopting cover cropping, and in subsequent years also adopted reduced tillage, the adoption rate for the combined activities (i.e., both activities on a given land area) should be used for that land.

To determine adoption rates for the purpose of re-calculating the weighted average or assessing whether a new practice not previously assessed in a given stratum is common practice, the project proponent should use the most current and highest quality data available (see Step 3 of Section 7 for further guidance on appropriate data sources). The project proponent may exclude their own activity instances from the adoption rate, so long as those instances have already been deemed additional and have been successfully verified at least once. In this way, the project proponent is not penalized for successful implementation of an activity in the region.

Where an activity is deemed common practice in a stratum through a re-calculated weighted average, growers that were previously implementing, and being credited for, the activity on a portion of their land should still be eligible to be credited for the expansion of the activity throughout their farm. However, any expansion in activity area should be included in current and future weighted average calculations in relation to eligibility of new growers, which will affect which other activities may be added without exceeding the 20 percent threshold.

Figure 5: Flowchart for establishing when the weighted average should be re-calculated with new activity instances for common practice demonstration



APPENDIX 4: GUIDANCE ON POTENTIAL EMERGING TECHNOLOGIES TO MEASURE SOC CONTENT

As indicated in Table 6 and Table 8 and the parameter tables (Section 9.2) related to modeled and measured SOC stocks, projects may use emerging technologies to determine SOC content where sufficient scientific progress has been achieved in calibrating and validating measurements, and uncertainty is well described. This appendix provides guidance on requirements for using such emerging technologies and a non-exhaustive list of potential technologies (with a focus on proximal sensing) to determine SOC content and criteria to ensure their robustness and reliability.[48]

The applicability of a selected technology to measure SOC in a project must be demonstrated in at least three peer-reviewed scientific articles. Project proponents must provide evidence of the ability of an emerging technology to predict SOC content with sufficient accuracy through the development and application of adequate calibration with data obtained from classical laboratory methods, such as dry combustion. The site characteristics for the underlying calibration must match the project site conditions, including range of SOC stocks, soil types and land use. While projects may use the services of companies measuring SOC, the specificities of the applied measurement technology, including calibration methods, must be made available for review by the VVB. Access must not be restricted through intellectual property rights.

Table 9 presents potential emerging proximal sensing technologies which research and publications have shown to hold promise for streamlining SOC measurement. Although proximal sensing techniques may not be as precise per individual measurement compared to conventional analytical laboratory methods (e.g., dry combustion), proximal sensing may be more cost-efficient and provide a better balance between accuracy and cost.[49] Hence, although each individual measurement may be less accurate, many more measurements may be made across time and space than would be feasible with conventional methods, enabling an overall estimate of SOC stock that is of similar or better accuracy than lower density sampling measured with conventional analytical laboratory methods. Since many more proximal devices may be used in a project than would be used were all samples sent to a single lab, care must be taken to demonstrate device-to-device calibration and precision. Project proponents must provide details to the VVB on the criteria and considerations of the emerging SOC measurement technology as specified in the list below and in Table 9.

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[48] The listed technologies may be updated in future versions of VM0042. The use of remote sensing-based techniques for estimating SOC content is currently not allowed.

[49] A detailed comparison of cost-effectiveness of dry combustion and three MIR and Vis-NIR instruments was conducted by Li, S., Viscarra Rossel, R. A., & Webster, R. (2022). The cost-effectiveness of reflectance spectroscopy for estimating soil organic carbon. *European Journal of Soil Science*, *73*(1), e13202. https://doi.org/10.1111/ejss.13202

Projects must maintain adherence to these criteria over time to ensure that measurement and remeasurement are conducted under the same conditions and are thus comparable.

The following information must be included in the monitoring plan and reports where emerging technologies are applied:

1) Standard Operating Procedures for sample processing (including drying, sieving, rock and root removal, grinding) and analysis adapted to the proximal sensing technique to be applied
2) For in-field or laboratory measurements without sample processing, a detailed explanation of strategies to overcome potential measurement obstacles due to signal interference related to differences in soil moisture, soil aggregates, sunlight, shadow, coarse fragments etc.
3) Description of the technology and specific equipment and instrument to be applied, including spectral range covered by the instrument applied and the actual resolution of the measurements
4) Description of pretreatment or preprocessing methods to analyze raw spectral data
5) Description of the modeling approach applied for estimating SOC content based on proximal sensing data, including model type (e.g., partial least squares regression) and model features/parameters
6) Description of randomized data-splitting for model calibration/training and validation/testing. Commonly, 70 percent of the sample data will be used for calibration/training and 30 percent for validation/testing. Other methods for data-splitting may be K-fold cross-validation and bootstrapping.
7) Demonstration that calibration and validation data are representative of the actual project area in terms of SOC content, clay type, clay content, Munsell soil color[50] and application of organic amendments, where relevant.[51] For field-moist measurements, extensive verification of predictive performance across a wide range of moisture contents is required.
8) Goodness-of-fit metrics and descriptive statistics from the dataset, such as RMSE, R2, RPIQ, bias and Lin's CCC or other suitable parameters
9) Description of the approach that will be used to generate posterior predictive distributions (PPDs) or intervals which will be used to propagate error from the spectroscopy model to calculations of the uncertainty deduction. PPDs may be based on Bayesian modeling methods that incorporate parameter uncertainty in the calibration/validation phase. Alternatively, PPDs may be based on estimates of model uncertainty derived by comparing results of dry combustion analysis for 10–15 percent of the samples from the project area to estimate SOC via spectroscopy at every verification event.
10) Demonstration that samples must be chosen in an unbiased manner such that they are representative of the project conditions and sampling design. For example, where a stratified

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[50] The Munsell Color Value describes a soil's color based on the following properties: hue (basic color), chroma (color intensity) and value (lightness).

[51] SOC content from sample units in which organic amendments are applied should be measured after thorough soil sample homogenization and grinding.

random sampling approach is employed, selection of points should be area-weighted based on the area of each stratum relative to the total project area.

Table 9: Method-specific criteria to evaluate the use of emerging technologies based on proximal sensing to measure SOC content

Method	Criteria and Considerations to Ensure Robustness and Reliability
Inelastic neutron scattering[52] (INS)	• Where carbonates are present (calcareous or limed soils), inorganic C must be separately accounted for. • Inorganic gamma scintillators (detectors based on sodium iodide NaI(Tl), bismuth germinate BGO and lanthanum bromide $LaBr_3$(Ce)) are better suited due to their higher efficiency of registering gamma rays in the energy range up to 12 MeV. • Pulsed fast/thermal neutron analysis (PFTNA) is the most suitable for soil neutron-gamma analysis. It allows separation of the gamma ray spectrum due to INS reactions from thermal neutron capture and the delay activation reaction spectra.
Laser-induced breakdown spectroscopy (LIBS)	• Soil samples must be dried for at least 24 h at 40 °C or air-dried for at least 48 h at room temperature. • Where carbonates are present (calcareous or limed soils), samples must be acid-washed. • Soil samples must be milled for homogenization and particle size reduction to facilitate the evaporation and atomization process in the plasma. • Before analysis, soil material must be pressed to form a pellet with a flat surface. • The configuration of the LIBS instrumental parameters must be optimized for each matrix. The laser pulse energy and the diameter of the laser beam (i.e., spot size) must be monitored simultaneously in the laser pulse fluence term (laser pulse energy per unit area, J cm^{-2}) as well as delay time, laser repetition rate etc. • Projects may rely on chemometric methods for signal analysis, spectral preprocessing and subsequent data processing and interpretation, including reducing matrix effects. • Multiple linear regression has proven to be an effective calibration strategy to tackle interference in soil carbon analysis. Further "non-traditional calibration strategies"[53] may be applied, which explore the plasma physicochemical properties, the use of analyte emission lines/transition energies with different sensitivities, the accumulated signal intensities and multiple standards to obtain a linear model or calibration curve. • Useful techniques for spectra pre-treatment include partial least squares analysis, artificial neural networks and removing the interference of iron and aluminum. • Multiple laser shots per sample may improve the measurement results.

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[52] Also known as neutron-stimulated gamma ray analysis or spectroscopy

[53] Described in Fernandes Andrade et al. (2021) and Costa et al. (2020)

Mid-infrared (MIR) and visible near-infrared (Vis-NIR and NIR) spectroscopy, including diffuse reflectance spectroscopy (DRS) and diffuse reflectance infrared Fourier transform (DRIFT) measurements	• For MIR and NIR, soil samples must be air or oven-dried and crushed or sieved to a size fraction smaller than 2 mm. • Measurement protocols must be used where available, such as Appendix B in Viscarra Rossel et al. (2016) for Vis-NIR or the Standard Operating Procedures of the Soil-Plant Spectral Diagnostics Laboratory of World Agroforestry Centre (ICRAF). • Calibration through multivariate statistics or machine-learning algorithms has been performed using large spectral libraries[54] or new site-specific libraries developed with local soil samples and higher accuracy. Sub-setting or stratifying the dataset may provide better calibration results. See England and Viscarra Rossel (2018) and Stevens et al. (2013) for further guidance on calibration techniques and spectroscopic model development and validation.

The following scientific publications provide more detail and further guidance on the application of the above-listed technologies to measure SOC:

INS

Izaurralde, R. C., Rice, C. W., Wielopolski, L., Ebinger, M. H., Reeves III, J. B., Thomson, A. M., Harris, R., Francis, B., Mitra, S., Rappaport, A. G., Etchevers, J. D., Sayre, K. D., Govaerts, B., & McCarty, G. W. (2013). Evaluation of three field-based methods for quantifying soil carbon. *PLoS ONE*, *8*(1), e55560. https://doi.org/10.1371/journal.pone.0055560

Kavetskiy, A., Yakubova, G., Prior, S. A., & Torbert, H. A. (2017). Neutron-stimulated gamma ray analysis of soil. In A. M. Maghraby (Ed.). *New insights on gamma rays*. Intech Open. Available at: https://www.intechopen.com/books/new-insights-on-gamma-rays/neutron-stimulated-gamma-ray-analysis-of-soil

Yakubova, G., Kavetskiy, A., Prior, S. A., & Torbert, H. A. (2019). Application of neutron-gamma analysis for determining compost C/N ratio. *Compost Science & Utilization*, *27*(3), 146–160. https://doi.org/10.1080/1065657X.2019.1630339

LIBS

Castro, J. P., & Pereira-Filho, E. R. (2016). Twelve different types of data normalization for the proposition of classification, univariate and multivariate regression models for the direct analyses of alloys by laser-induced breakdown spectroscopy (LIBS). *Journal of Analytical Atomic Spectrometry*, *31*(10), 2005–2014. https://doi.org/10.1039/C6JA00224B

Costa, V. C., Babos, D. V., Castro, J. P., Fernandes Andrade, D., Gamela, R. R., Machado, R. C., Sperança, M. A., Araújo, A. S., Garcia, J. A., & Pereira-Filho, E. R. (2020). Calibration strategies applied

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[54] Such as the African ICRAF-ISRIC Soil Spectra Library, the multispectral data collected in the European LUCAS topsoil database, the USDA NRCS (KSSL) National Soil Survey Center mid-infrared spectral library and the Australian soil visible near infrared spectroscopic database described in Viscarra Rossel and Webster (2012)

to laser-induced breakdown spectroscopy: A critical review of advances and challenges. *Journal of the Brazilian Chemical Society*, *31*(12), 2439–2451.

Fernandes Andrade, D., Pereira-Filho, E. R., & Amarasiriwardena, D. (2021). Current trends in laser-induced breakdown spectroscopy: A tutorial review. *Applied Spectroscopy Reviews*, *56*(2), 98–114. https://doi.org/10.1080/05704928.2020.1739063

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APPENDIX 5: DEFINITIONS OF SOIL SLOPE CLASSES FOR USE IN SETTING BASELINE CONTROL SITES

Table 10: Soil slope classes

Classes for—		Slope (Gradient) Class Limits	
Simple Slopes	Complex Slopes	Lower (%)	Upper (%)
Nearly level	Nearly level	0	3
Gently sloping	Undulating	4	8
Strongly sloping	Rolling	9	16
Moderately steep	Hilly	17	30
Steep	Steep	31	45
Very steep	Very steep	>45	

Adapted from USDA Natural Resource Conservation Service (NRCS) (2017). *Soil Survey Manual Handbook No. 18* Chapter 2.—Landscapes, Geomorphology, and Site Description Table 2-3. Available at: https://www.nrcs.usda.gov/resources/guides-and-instructions/soil-survey-manual

Workflow for a Slope Analysis in a GIS

1) Data required: digital elevation model (DEM) as a raster data layer of horizontal and vertical resolution suitable for the extent of the area of interest, and coordinate reference system in meters
2) Tools required: GIS software suitable for processing raster data (e.g., QGIS, ArcGIS, SAGA GIS, GRASS, GDAL)
3) Load the DEM data layer onto the software.
4) Construct a slope (in percent) layer from the DEM.
5) Reclassify the slope layer into discrete slope classes using the class limits listed in Table 10.
6) Determine the coverage of – or, equivalently, the number of pixels occupied by – each slope class and identify the dominant slope class (i.e., the slope class with the largest coverage or highest number of pixels occupied).

APPENDIX 6: ADDITIONAL UNCERTAINTY EXAMPLES

Staged sampling designs and alternative measurement approaches are valid and may be applied under this methodology, but stratified random sampling is the required sampling strategy at the stage during which sample points are selected (see Section 8.2.1). In this appendix, an example based on a multi-stage design for a grouped project with multiple landowners with multiple fields is provided. At the final stage, the sampling points are determined randomly within predefined strata, thus following the stratified random sampling strategy.

In such projects, landowners and fields may be dispersed across large geographic areas. Aggregating these fields into a total project area that is then simply divided into strata may prove inefficient and may provide a poor estimate of uncertainty. It would likely result in small numbers of samples being placed in each field, underestimating small-scale variability of change in carbon within fields. Furthermore, since the field is the level at which improved management is typically implemented, ensuring that fields are represented as sampling units within the sampling design may be more appropriate.

In this example design, the stages/units are as follows:

1) Landowner, presuming they have multiple fields enrolled in a project that have the same baseline and project scenarios and similar physical conditions
2) Fields, selected using a probability proportional to size (with replacement) procedure
3) Within-field strata, designed based on physical (e.g., topographic indices) or soil data (e.g., clay content)
4) Points, selected within strata using simple random sampling (with replacement)

The same sources of error apply in this example as in the examples provided in Section 8.6, but the uncertainty estimator for sampling error should be changed to match this alternative design. Below are similar sets of equations for both uncertainty estimation approaches allowed under Quantification Approach 1 and the approach under Quantification Approach 2. Additionally, an example is provided under Quantification Approach 2 in which soil spectroscopy methods are used to measure SOC content and the MC simulation method is used to propagate measurement errors from use of these methods through calculations of the uncertainty deduction.

Quantification Approach 1 – Analytical Error Propagation

$$s^2_{sampling,\Delta\bullet,t} = \sum_{f=1}^{F} s^2_{sampling,\Delta\bullet,ft} \qquad \text{(A6.1)}$$

$$s^2_{sampling,\Delta\bullet,ft} = \frac{1}{k_f\left(k_f - 1\right)} \sum_{j=1}^{k_f} (\Delta\bullet^*_{fj} - \Delta\bullet^*_{f})^2$$

Note – notation for time period t *is suppressed hereafter for convenience.*

Where:

$$\Delta\bullet^*_{fj} = \frac{A_f}{A_{fj}} \sum_{h=1}^{H_{fj}} \frac{A_{fhj}}{n_{fhj}} \sum_{i=1}^{n_{fhj}} \Delta\bullet_{fjhi}$$

$$\Delta\bullet^*_{f} = \frac{1}{k_f} \sum_{j=1}^{k_f} \Delta\bullet^*_{fj}$$

And:

$s^2_{sampling,\Delta\bullet,t}$ = Variance of emission reductions in gas or pool • due to sampling error at time *t* across the entire project area (t CO_2e)^2

$s^2_{sampling,\Delta\bullet,ft}$ = Variance of emission reductions in gas or pool • due to sampling error for farmer *f* (i.e., the primary sampling unit) at time *t* (t CO_2e)^2

$\Delta\bullet^*_{fj}$ = Estimated emissions reduction in gas or pool • for farmer *f* across their total land area based on data collected at time *t* in field *j* (t CO_2e)

$\Delta\bullet^*_{f}$ = Average estimated emissions reduction in gas or pool • for farmer *f* across their total land area based on data collected at time *t* across all fields *k* (t CO_2e)

$\Delta\bullet_{fjhi}$ = Estimated emissions reduction in gas or pool • in year *t* at point *i* on an area basis in stratum *h* in field *j* for farmer *f* (t CO_2e/ha)

h = 1, …, H_j strata in field *j* for farmer *f*

i = 1, …, n_{fhj} sample points within stratum *h* and field *j* for farmer *f*

j = 1, …, k_f fields selected for sampling for farmer *f*

f = 1, …, *F* farmers in the project

A_{fhj} = Area of stratum *h* and field *j* for farmer *f*

A_{fj} = Area of field *j* for farmer *f*

A_f = Total area for farmer *f*

Model errors are assumed to be uncorrelated with the input data in the sample and to be independent across samples. Then, the variance of $\overline{\Delta \bullet_t}$ incorporating sample uncertainty and model prediction uncertainty is the sum of variances due to sampling and model error divided by the square of the total project area:

$$s^2_{\overline{\Delta \bullet},t} = \frac{s^2_{sampling,\Delta \bullet,t}}{A^2} + s^2_{model} \tag{A6.2}$$

Quantification Approach 1 – Monte Carlo Error Propagation

Similar to the MC error propagation example provided in Section 8.6.1.2, both model prediction error and sampling error are estimated from a set of L estimates of the true total GHG emissions across the entire project. For convenience, introductory text from Section 8.6.1.2 is included here again. Likewise, notation in this section differs from the rest of the methodology to better match conventions in Bayesian statistics. Notation to denote time *t* is suppressed for convenience and to avoid confusion with the use of τ.

For a particular time period and emission source, the estimand, or target parameter of interest, is the true total GHG emission reduction across the entire project, denoted as τ, in tonnes of carbon dioxide equivalent (t CO_2e). The estimate of τ produced through MC simulation is denoted by $\hat{\tau}$. Similarly, the areal mean GHG ERR is denoted by μ (equivalent to $\Delta \bullet_t$) in t CO_2e/unit area Estimates of μ are denoted as $\hat{\mu}$. Since model prediction error is implicitly incorporated into the MC simulations through parameter uncertainty, these estimates may then be used to estimate sampling and model prediction error based on the realized sample *s* and the sampling design employed.

First, to generate an estimate ($\hat{\tau}$) of τ, GHG emissions are simulated under the baseline and project scenarios multiple times at each sample point, indexed by $l = 1, \ldots, L$. The GHG ERRs at each point are then calculated as the difference between predicted GHG ERRs under baseline and project scenarios. These estimates are used to produce an estimate of emissions reductions ($\tilde{y}$) at each point, similarly indexed by l following Equation A6.3 below.

$$\tilde{y}_{fjhil} = \tilde{z}_{bsl,fjhil} - \tilde{z}_{pr,fjhil} \tag{A6.3}$$

Where:

$\tilde{y}_{fjhil}$	=	Predicted emissions reduction for the lth simulation at point *i* in stratum *h* in field *j* for farmer *f* (t CO_2e/ha)
$\tilde{z}_{bsl,fjhil}$	=	Predicted GHG ERRs in the baseline scenario for the lth simulation at point *i* in stratum *h* in field *j* for farmer *f* (t CO_2e/ha)
$\tilde{z}_{pr,fjhil}$	=	Predicted GHG ERRs in the project scenario for the lth simulation at point *i* in stratum *h* in field *j* for farmer *f* (t CO_2e/ha)

Note – notation for the source of emissions and time period is suppressed. The sign convention is that $\tilde{z}_{bsl,fjhil}$ is emissions to the atmosphere in the baseline scenario. Thus, for the SOC pool, $\tilde{z}_{bsl,fjhil}$ is -1 times the predicted temporal change in SOC stocks in the baseline scenario; similarly, $\tilde{z}_{pr,fjhil}$ is -1 times the predicted temporal change in the project scenario.

The total set of L estimates of $\tilde{y}$ are then used to produce $\hat{t}$ and $\hat{\mu}$, according to Equation A6.4.

$$\hat{\mu} = \frac{\hat{t}}{A}$$

$$\hat{t} = \sum_{f=1}^{F} \hat{t}_f \tag{A6.4}$$

Where:

$$\hat{t}_f = \frac{1}{k_f} \sum_{j}^{k_f} \hat{t}_{fj}$$

$$\hat{t}_{fj} = \frac{A_f}{A_{fj}} \sum_{h=1}^{H_{fj}} \frac{A_{fhj}}{n_{fhj}} \sum_{i=1}^{n_{fhj}} \sum_{l=1}^{L} \tilde{y}_{fjhil}$$

And:

$\hat{t}_f$ = Monte Carlo estimate (MC mean) of GHG emissions reductions for a given source for farmer *f* (t CO2e)

$\hat{t}_{fj}$ = Monte Carlo estimate (MC mean) of GHG emissions reductions for a given source in field *j* for farmer *f* (t CO2e)

The total uncertainty is then decomposed into two components, sampling and modeling uncertainty. Using standard variance decomposition (i.e., the law of total variance) following Del Grosso et al. (2010), the total variance is decomposed according to Equation A6.5.

$$\mathrm{Var}(\hat{t}) = \mathbb{E}[\mathrm{Var}(\hat{t}|\boldsymbol{s})] + \mathrm{Var}(\mathbb{E}[\hat{t}|\boldsymbol{s}]) \tag{A6.5}$$

For the stratified random sampling design used in this example, the variance components are estimated according to Equation A6.6, which is area-weighted.

$$\widehat{Var}(\hat{t}) = \left\{ \sum_{f=1}^{F} s_{sampling,f}^2 \right\} + s_{model}^2 \tag{A6.6}$$

Where:

$$s^2_{sampling,f} = \frac{A_f^2}{k_f(k_f-1)}\sum_{j=1}^{k_f}(\hat{\tau}_{fj}-\hat{\tau}_f)^2$$

$$s^2_{model} = \frac{1}{L-1}\sum_{l=1}^{L}(\tilde{\tau}_l-\hat{\tau})^2$$

$$\tilde{\tau}_l = \sum_{f=1}^{F}\tilde{\tau}_{fl}$$

Where:

$$\tilde{\tau}_{fl} = \frac{1}{k_f}\sum_{j}^{k_f}\tilde{\tau}_{fjl}$$

$$\tilde{\tau}_{fjl} = \frac{A_f}{A_{fj}}\sum_{h=1}^{H_{fj}}\frac{A_{fhj}}{n_{fhj}}\sum_{i=1}^{n_{fhj}}\tilde{y}_{fjhil}$$

And:

$s^2_{sampling,f}$ = Variance of emission reductions in gas or pool • due to sampling error for farmer *f* (i.e., the primary sampling unit) at time *t* (t $CO_2e)^2$

$\tilde{\tau}_l$ = Monte Carlo estimate (MC mean) of GHG emissions reductions for a given source across the entire project area in the lth simulation (t CO_2e)

$\tilde{\tau}_{fl}$ = Monte Carlo estimate (MC mean) of GHG emissions reductions for a given source for farmer *f* in the lth simulation (t CO_2e)

$\tilde{\tau}_{fjl}$ = Monte Carlo estimate (MC mean) of GHG emissions reductions for a given source in field *j* for farmer *f* in the lth simulation (t CO_2e)

Lastly, the variance of the average GHG emission reduction $\left(\widehat{\mathrm{Var}}(\hat{\mu})\right)$ is obtained based on Equation A6.7.

$$\widehat{Var}(\hat{\mu}) = \sum_{f=1}^{F}\left\{\frac{1}{A^2}s^2_{sampling,f}\right\} + \left\{\frac{1}{A^2}s^2_{model}\right\} \qquad \text{(A6.7)}$$

Quantification Approach 2

The total variance of the estimate of mean SOC stock changes is based on the sum of variances of comparisons of project and baseline control plots for each farmer. Variance of SOC removal estimates for each farmer are based on the combined variance of the estimates of change over time in a given verification period *t*, for both the project and baseline scenarios. The covariance of these estimates is conservatively excluded as the baseline control sites and project sites are assumed to be independent.

Note that in these equations Δ is used to signify both emissions reduction in the SOC pool (i.e., project scenario SOC stocks minus baseline scenario SOC stocks) and changes in SOC stocks over time in both the baseline and project scenarios.

$$s^2_{\overline{\Delta SOC,t}} = \frac{1}{A^2}\sum_{f=1}^{F} s^2_{\Delta SOC,ft} \tag{A6.8}$$

Where:

$$s^2_{\Delta SOC,ht} = s^2_{\Delta SOC,pr,ft} + s^2_{\Delta SOC,bsl,ft}$$

And:

$s^2_{\Delta SOC,ft}$ = Variance of the estimate of total SOC stock changes in verification period *t* for farmer *f*, calculated as the difference in net change between the project and baseline scenarios over period *t* (t $CO_2e)^2$

$s^2_{\Delta SOC,pr,ft}$ = Variance of the estimate of total SOC stock changes in the project plots in verification period *t* for farmer *f*, calculated as the difference in SOC stocks at the beginning and end of period *t* (t $CO_2e)^2$

$s^2_{\Delta SOC,bsl,ft}$ = Variance of the estimate of total SOC stock changes in verification period *t* in baseline (control) plots paired with farmer *f*, calculated as the difference in SOC stocks at the beginning and end of period *t* (t $CO_2e)^2$

Because the sample design for the project and baseline control plots may be different, the uncertainty estimator should match the sample design used in the project and baseline control plots. For example, the project area may be monitored using a staged design if there are a substantial number of sampling units (e.g., fields) in the project area. But the baseline control plots may be fewer, meaning they can all be monitored and would not require a staged design. In such cases, baseline and project areas should use different uncertainty estimators before estimating the combined uncertainty. However, this example presumes that within each stratum, sample points are similarly determined using simple random sampling with replacement for both baseline and project, so the estimator in both should be the same.

Equation A6.9 provides an example for the project scenario. The variance of the estimate of the change is then a function of the variance and covariance of soil sampling results at both time points within verification period *t*. These time points are denoted as t_{final} and t_{start}, hereafter shortened to subscripts *x* and s.

Note – notation differs from Section 8.6.2 with x *being used instead of* f *to avoid confusion with subscript* f *indicating an individual farmer.*

$$s^2_{\Delta SOC,pr,ft} = s^2_{SOC,pr,fx} + s^2_{SOC,pr,fs} - 2COV(SOC_{pr,fx}\,;\,SOC_{pr,fs}) \tag{A6.9}$$

The variance for an individual farmer is estimated as follows. The same equation form applies to time t_{final}.

$$s^2_{SOC,pr,fs} = \frac{1}{k_f\left(k_f - 1\right)} \sum_{j=1}^{k_f} \left(SOC^*_{pr,fsj} - SOC^*_{pr,fs}\right)^2$$

$$SOC^*_{pr,fsj} = \frac{A_f}{A_{fj}} \sum_{h=1}^{H_{fj}} \frac{A_{fhsj}}{n_{fhsj}} \sum_{i=1}^{n_{fhsj}} SOC_{pr,fhsji}$$

$$SOC^*_{pr,fs} = \frac{1}{k_f} \sum_{j=1}^{k_f} SOC^*_{pr,fsj}$$

$$COV\left(SOC_{pr,fs}\,;\,SOC_{pr,fx}\right) = \frac{1}{k_f\left(k_f - 1\right)} \sum_{j=1}^{k_f} \left(SOC^*_{pr,fsj} - SOC^*_{pr,fs}\right)\left(SOC^*_{pr,fxj} - SOC^*_{pr,fx}\right)^2$$

And:

$s^2_{SOC,pr,fx}$ = Variance of the estimate of SOC stocks in the project scenario at t_{final} for farmer f (t CO_2e)^2

$s^2_{SOC,pr,fs}$ = Variance of the estimate of SOC stocks in the project scenario at t_{start} for farmer f (t CO_2e)^2

$COV\left(SOC_{pr,fs}\,;\,SOC_{pr,fx}\right)$ = Covariance of estimates of SOC stocks at t_{final} and t_{start} in the project scenario for farmer f (t CO_2e)^2

$SOC^*_{pr,fsj}$ = Estimated SOC stocks for farmer f across their total land area based on data collected at t_{start} for farmer f in field j (t CO_2e)

$SOC^*_{pr,fs}$ = Average estimated SOC stocks for farmer f across their total land area based on data collected at t_{start} for farmer f across all fields k (t CO_2e)

SOC_{fhsji} = Estimated SOC stock equivalent at point i in stratum h in field j for farmer f at t_{start} (t CO_2e)

A_{fhsj} = Area of stratum h and field j for farmer f at t_{start}

DOCUMENT HISTORY

Version	Date	Comment
v1.0	19 Oct 2020	Initial version
v2.0	30 May 2023	• Introduction of a baseline control sites option to allow for direct SOC measurement under Quantification Approach 2 • Update of Section 8.6 on uncertainty assessment to clarify statistical procedures and align with the *VCS Methodology Requirements* • Introduction of guidance on the use of proximal sensing technologies to estimate SOC content in Appendix 4 • Introduction of an applicability condition allowing for one-time land conversion from grassland to cropland or vice versa to restore degraded lands in Section 4 and Appendix 2 • Introduction of a requirement and procedures to account for emissions associated with use of agricultural limestone in Section 8.2.4 • Introduction of a requirement to account for leakage from diversion of biomass residues used for energy applications in the baseline scenario • General improvements, errata and clarifications