Verified Carbon Standard

Draft VCS Methodology

VM0032

SUSTAINABLE NATIVE GRASSLANDS MANAGEMENT THROUGH ADJUSTMENT OF FIRE AND GRAZING

Draft Version 2.0

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Sectoral Scope 14: AFOLU

Version 1.0 of this methodology was developed by Soil for the Future in partnership with The Nature Conservancy and Fauna & Flora International.

The draft version 2.0 of this methodology was developed by Soils for the Future, LLC and Verra.

CONTENTS

1 SUMMARY DESCRIPTION

Additionality, Crediting Method, and Mitigation Outcome	
Additionality	Activity Method
Crediting Baseline	Project Method
Mitigation Outcome	Reductions and Removals

This methodology applies to project activities that aim to increase soil organic carbon (SOC) stocks and reduce methane and nitrous oxide emissions by improving grazing and/or fire management. Project activities may occur in grasslands, savannas, and grassy woodlands.

Project proponents must use a combination of the following three quantification approaches:

Measured Approach: Direct measurement is used to quantify changes in SOC and woody biomass carbon stocks. The baseline scenario is measured and remeasured directly at baseline control sites. The measured approach is only applicable to SOC and woody biomass carbon. Projects may have reduced uncertainty compared to those following a modeled approach, however, verification of GHG emission reductions ("reductions") is feasible only after increases in soil carbon are detected, likely every five or more years, depending on site productivity.

Modeled Approach: An acceptable model is used to estimate GHG flux based on soil characteristics, grazing pressure, initial SOC stocks, and climatic conditions. The appropriate use of biogeochemical modeling for SOC quantification must be approved (see Appendix 3). SOC stocks must be measured every five years or more frequently. The remeasurement data is used to re-estimate model prediction error and recalibrate the model (i.e., "true-up").

Default Factors: CO_2 flux from fossil fuel combustion and N_2O and CH_4 fluxes from livestock are calculated using default emission factors.

2 SOURCES

This methodology uses the most recent versions of the following Verified Carbon Standard (VCS) module and tools:

- *VMD0053 Model Calibration, Validation, and Uncertainty Guidance for the Methodology for Improved Agricultural Land Management*
- *VMD0054 Module for Estimating Leakage from ARR Activities*
- *VT0008 Additionality Assessment*

- *VT0014 Estimating Organic Carbon Stocks Using Digital Soil Mapping*
- VCS *AFOLU Non-Permanence Risk Tool*

This methodology uses the most recent version of the following Clean Development Mechanism (CDM) tool:

- CDM A/R methodological tool *Calculation of the number of sample plots for measurements within A/R CDM project activities*

3 DEFINITIONS

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

Baseline period
The historical reference period over which a project's baseline emissions are calculated, consisting of the ten consecutive years occurring immediately before the project start date

Calibration
Any process involving the adjustment of parameters and constants within a model so that the model more accurately simulates measured values

Cellulose
Carbon-rich plant material that is decomposed by special enzymes (cellulases) typically found only in certain fungi, bacteria, or other microorganisms

Enteric methane
Methane emissions from ruminants, due to enteric fermentation of feed

Equilibrium
State of a carbon pool where inputs to the pool are balanced by outputs (e.g., when inputs to soil organic matter are balanced by losses from respiration by microorganisms)

Exclosure
Fence or other device that excludes grazing animals from an area

Fire management
Set of practices that either inhibit or cause fire to achieve desired goals and objectives for vegetation and soil carbon

Grazing animal
Mammal that eats primarily herbaceous plants or the leaves of shrubs

Lignin
Carbon-rich plant material that is generally resistant to decomposition by microorganisms

Overgrazing
Grazing that:

- has reduced vegetation cover such that more than 80% bare ground is exposed, and/or
- consumes more than 75% of production, resulting in changes in persistent vegetation from mostly palatable to unpalatable species.

Prescribed fire
Fire set intentionally as part of a specific strategy to manage vegetation

Reassessment period
Under a modeled approach, the time in years between the project start date or previous model reassessment and the point at which carbon stocks are remeasured at all sampling points in order to reassess and possibly recalibrate the soil carbon dynamic model. May be much longer than the initial verification period to allow sufficient time for measurable changes in carbon stocks to occur.

Rotational grazing
Grazing in which grazing animals are aggregated or clustered by herding or fencing to small portions (<25%) of available grazing lands for relatively short periods of time, followed by movement to new portions of available grazing land. Designed to allow forage plant species sufficient time and resources (water, nutrients) to regrow and set seed following grazing or to complete growth and set seed before grazing.

Soil organic carbon (SOC) density
Area-specific amount of carbon in the soil, expressed as a mass per unit area to a designated depth

Soil carbon dynamic model
A model published in the peer-reviewed scientific literature that predicts changes in soil organic carbon (SOC) density as a function of various input variables, which may include aboveground production, belowground production, precipitation, temperature, fire frequency, initial SOC, soil texture, and grazing intensity and possibly other factors detailed in the peer-reviewed article(s) describing the model.

4 APPLICABILITY CONDITIONS

This methodology applies globally to project activities that adjust the number, type, and husbandry practices of grazing animals, adjust grazing practices, adjust the frequency, intensity and timing of fires, and/or introduce herbaceous grassland species as potential forage for grazing animals or to restore degraded soils. These activities must occur on land used as grasslands per the conditions specified below, and must demonstrably reduce net GHG emissions from grassland ecosystems by increasing soil and/or aboveground woody carbon stocks, reducing N_2O emissions, and/or reducing CH_4 emissions.

The methodology is applicable under the following conditions:

1) The project area is natural, untilled grass-dominated bushlands, rangelands, savannas, or grassy woodlands in the baseline and project scenarios (see table 1).

2) Where the baseline scenario land use includes croplands, shrublands, woodlands or degraded land that do not classify as eligible (see table 1), the project proponent must demonstrate that the project area falls into a Grassland, Savanna, or Woodland biome classification using the Terrestrial Ecoregions of the World (TEOW) and/or the IUCN Global Ecosystem Typology[1].

3) The project area is grazed and/or subject to fires in the baseline and/or project scenarios.

4) Baseline emissions derived from livelihood-driven human impacts on aboveground woody biomass (e.g., cutting for fuel wood, charcoal, or timber sales) are less than 5% of total baseline and project emissions

Note — Lands may be used for different purposes in the baseline and project scenarios. Examples include:

a) *switching from livestock husbandry to wildlife conservation and associated tourism (re-wilding).*

b) *switching from hay production to livestock husbandry.*

c) *switching from continuous grazing to some form of rotational grazing.*

d) *restoring degraded grasslands or lands previously converted from grassland to urban, cropland, or other uses by seed addition (without cultivation).*

e) *switching from one livestock species to* another*, such as from sheep and goats to camels.*

[1] IUCN GET is a hierarchical, comprehensive classification system that categorizes ecosystems

TEOW is similar and works with ecoregions as the main spatial data, classified into 14 different biomes such as forests, grasslands, or deserts. 4/14 biomes are grasslands:

- Tropical and Subtropical Grasslands, Savannas, and Shrublands
- Temperate Grasslands, Savannas, and Shrublands
- Flooded Grasslands and Savannas
- Montane Grasslands and Shrublands

f) shifting the season of burning from late to early in the dry season.

g) reducing the frequency of fires.

h) conservation of heavily poached and reduced wildlife populations to increase grazing and reduce fuel loads, thus reducing frequency of fires.

Table 1. Eligible savanna and grasslands ecosystems

Ecosystem Type	Tree Canopy Cover (%)	Tree Height (m)	Herbaceous Production (g/m²)	Characteristics
Woodland	<50	>5	>100	Intermediate canopy; mix of trees and grasses
Savanna	<50	>5	>100 (dominated by grass)	Grassland with scattered tall trees
Grassland	<10	N/A	>100 (dominated by herbaceous vegetation)	Little to no tree canopy
Grassy woodland	>50	>5	>100	Qualifies as forest by canopy cover, but with substantial grass understory
Rangeland/ Bushland	Variable, <50	Woody plants <5 m may be present	>100	Includes areas with significant low woody vegetation and grass cover; can vary under different scenarios

This methodology is not applicable under the following conditions:

5) The project results in more than a 1% increase in the proportion of the total project area over which animal dung covers more than 50% of the ground (and thus decomposes anaerobically) such as feedlots, or corrals or bomas that are used nightly,

6) Project activities include tillage for crop production or re-seeding.

7) Project activities include input of materials (fertilizer, dung, etc.) to increase nitrogen availability in soil.

5 PROJECT BOUNDARY

The project area includes all areas where grassland management activities are implemented. The project area boudary and all designated strata (see Section 8.2.3) must be delineated by topologically corrected geographic information system (GIS) polygons, represented as .kml or .shp files. These files must be available at validation.

Table 2. Carbon pools accounted for in the project boundary and as leakage

Carbon pool	Included?	Justification/ Explanation
Aboveground woody biomass	Yes/Optional	Where project activities involve changes in fire management, the project proponent must monitor changes in aboveground woody plant biomass. Where fire frequency is reduced, there may be increases in removals to woody biomass. Where fire frequency is increased, carbon stocks can be dramatically reduced because woody plants in some savanna grasslands can account for 10–30% of carbon stocks (Holdo et al. 2009). Managing grazing may increase herbaceous fuel biomass, therefore making fires more likely. Where project activities do not involve changes in fire management, quantification and monitoring of aboveground woody biomass carbon stock changes is optional.
Aboveground herbaceous biomass	No	Aboveground herbaceous biomass is typically burned or decomposed within the same year of its production and therefore is not a major sink. It is considered in balance with CO_2 uptake, respiration by plants, and annual decomposition.
Belowground biomass	No	Belowground non-woody biomass typically decomposes within 1–2 years of its production and therefore is not considered a major sink in grasslands. It is considered in balance with CO_2 uptake, respiration by plants, and annual decomposition. As tillage is not permitted under this methodology, any increase from project activities may be conservatively excluded.
Dead wood	No	Negligible in grasslands, particularly those with fire
Litter	No	In grasslands, litter exhibits high turnover which reflects balance with CO_2 uptake, respiration by plants, and annual decomposition.
Soil organic carbon (SOC)	Yes	Major carbon pool affected by sustainable grassland management though adjustment of fire and grazing
Wood products	No	Negligible in untilled grasslands

Carbon pools and GHG emission sources may be deemed de minimis where it is demonstrated that the combined decrease in carbon stocks or increase in GHG emissions amounts to less than 5% of the total GHG benefit generated by the project (see Appendix 1).

The greenhouse gas sources and sinks accounted for, including as leakage, are shown in Table 3.

Project proponents must evaluate whether new emissions result from project activities and whether these emissions meet de minimis criteria (see Appendix 1).

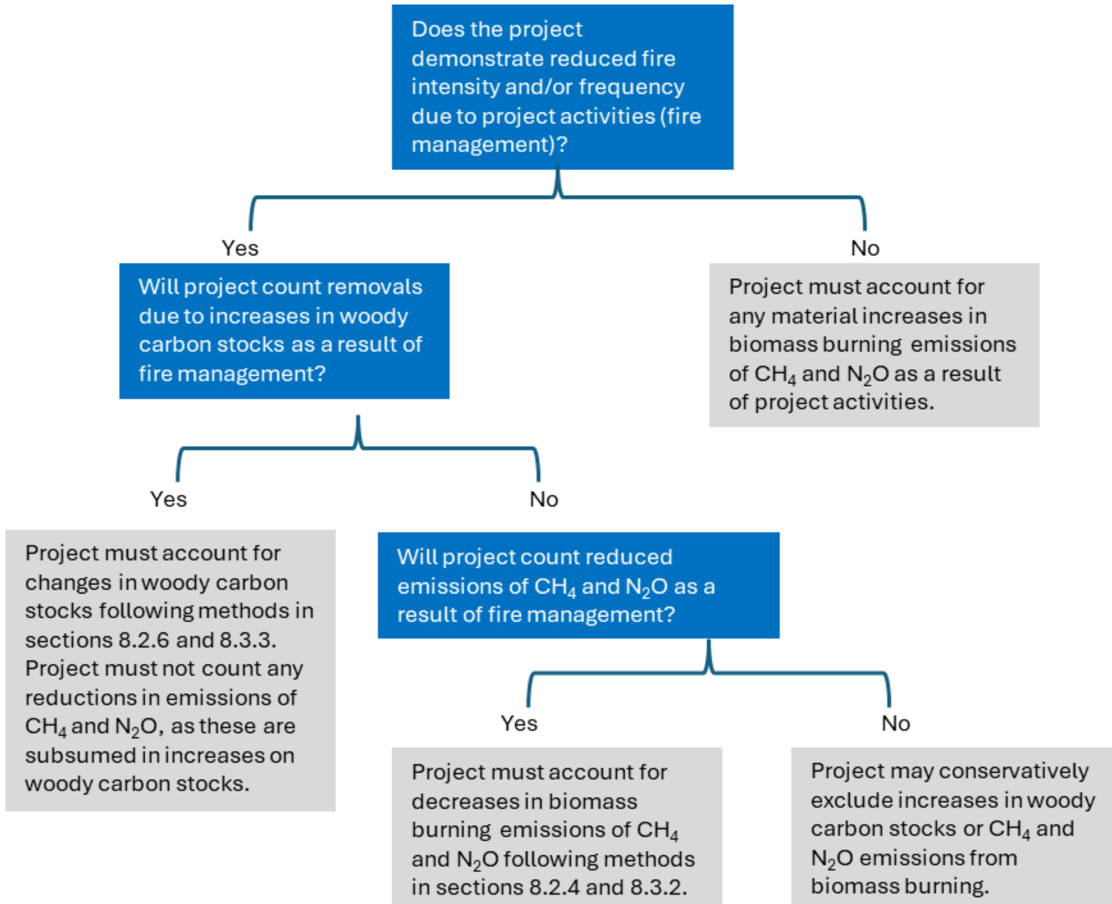
Table 3. GHG sources and sinks accounted for as baseline, project, and leakage emissions

Source/Sink		Type	Gas	Included?	Justification/Explanation
Baseline	Animal grazing	Source	CO_2	No	Balanced with CO_2 uptake, respiration by plants, and annual decomposition
		Source	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.
		Source	N_2O	No	No increase in concentration of dung and forage if not fertilized (see applicability conditions)
	Biomass burning	Source	CO_2	No	Balanced with CO_2 uptake by plants
		Source	CH_4	Optional	Biomass burning activities may increase emissions above the *de minimis* threshold, subject to project activities and whether increases in aboveground plant biomass carbon from project activities are conservatively excluded.
		Source	N_2O	Optional	
	Soil emissions	Source	CO_2	No	Assumed to be in balance with carbon inputs to soil organic carbon (SOC at equilibrium)
		Source	CH_4	No	Negligible
		Source	N_2O	No	Negligible
	Dung decomposition	Source	CO_2	No	Assumed to be in balance with carbon inputs to dung
		Source	CH_4	Yes	Anaerobic decomposition of dung in confined spaces such as corrals/bomas
		Source	N_2O	Yes	Anaerobic decomposition of dung in confined spaces such as corrals/bomas

Project	Animal grazing	Source	CO_2	No	Balanced with CO_2 uptake by plants
		Source	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
		Source	N_2O	No	Negligible on grass-covered soils
	Burning biomass	Source	CO_2	No	Balanced with CO_2 uptake by plants
		Source	CH_4	Yes/No	Where reducing or maintaining fire is a project activity, these sources may be conservatively excluded. Otherwise, source must be included. Where project activities lead to an increase in woody plant carbon stocks and these are counted towards removals, decreases in CH_4 and N_2O emissions are not counted as they are assumed to be included in aboveground woody biomass carbon stock.
		Source	N_2O	Yes/No	
	Soil emissions	Source	CO_2	No	Accounted for in measured change in SOC
		Source	CH_4	No	Negligible
		Source	N_2O	No	Negligible
	Dung decomposition	Source	CO_2	No	Assumed to be in balance with carbon inputs to dung
		Source	CH_4	Yes	Anaerobic decomposition of dung in confined spaces such as corrals/bomas
		Source	N_2O	Yes	Anaerobic decomposition of dung in confined spaces such as corrals/bomas
	Fossil fuel	Source	CO_2	Yes/No	Sources of fossil fuel emissions are vehicles and mechanical equipment required by the project activity. Must be included where emissions increase significantly in the project compared to the baseline scenario (see Appendix 1). Otherwise it may be excluded.

Figure 1 presents a decision matrix to determine whether biomass burning is accounted for as fire emission change or a carbon stock change. Sources and carbon pools must be selected accordingly.

Figure 1. Selection of carbon pools and emission sources related to the accounting of biomass burning



6 BASELINE SCENARIO

To develop the baseline scenario, project proponents must document historical fire and grazing activities in the project area, using published or collected project-specific data and/or models. Table 4 lists appropriate methods of documentation and Section 9.3 provides more information on monitoring. Project proponents must provide evidence of baseline vegetation conditions and demonstrate how these are linked to historical management activities.

Table 4. Methods to document historical fire and grazing activities in the project area

Baseline Scenario Indicator	Data collection	Methods
Historic grazing activities	Required	Where project activities focus on grazing management, project proponents must document grazing activities prior to the start of the project. Acceptable methods include interviews with grazing management decision makers, documented grazing plans, or records of numbers and locations of grazing animals. In communal grazing systems, narratives of livestock numbers and previous locations supplied by community leaders may be used to reconstruct grazing histories.
Livestock surveys of abundance/ density	Required	Project proponents must provide livestock numbers sorted by species, age (adult or juvenile), and sex (where data are available) from at least four years across the ten-year period prior to the project start. These must be obtained from one of the following sources: 1) Producer records 2) Livestock censuses conducted by researchers, government or the project proponent 3) Where the project is conducted in communal grazing systems, household surveys in which livestock owners recall past livestock numbers. Where surveys are employed, a representative sample of households must be visited (30–1000 households, with a target of 3% of total households including those without livestock). Where project area-specific past livestock numbers are not available, regional or country-specific censuses may be applied, provided the data used are associated with the same livestock practice (on grasslands that meet the applicability conditions of this methodology).
Ground measurements of grazing impacts	Optional	Ground measurements of past grazing impacts should be determined by estimating longer-term impacts of grazing via indicators (e.g., proportion of bare ground, relative proportions of annual versus perennial grasses) compared with areas without livestock (e.g., experimental exclosures or areas inside protective fences or areas that have excluded livestock) for at least 10 years prior to the project start. Ground-based indicators must be justified with peer-reviewed literature or published government reports applicable to the project area, as well as the methods used to assess the relative change.

Baseline Scenario Indicator	Data collection	Methods
Remotely sensed measurements of grazing impacts	Optional	Interpretations of satellite imagery (Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), or other similar indices, e.g., Liu et al. (2007); Ren et al. (2011)) may be used to assess past impacts from livestock grazing on vegetation quality. Where this method is selected, images used must: 1) cover at least four intervals across the 10 years prior to the project start date. 2) include at least one image from 8–10 years prior to the project start date.
Methane emissions	Required	Detailed surveys of livestock (see above) and an average body weight for each livestock category[2]
Fire frequency/ intensity	Required	Altered fire regimes have been directly related to changes in soil carbon in many areas of the world (Pellegrini et al. 2023). Where adjustments in fire frequency and/or intensity are a project activity, project proponents must demonstrate a fire history that includes: 1) a map of areas that burned. 2) the season of burning. 3) the number of times each area burned over the previous ten years prior to the project start date. This may be obtained using satellite products that provide polygons of burned areas for 15-day periods throughout the dry or burning season (e.g., MODIS Burned Area Product,[3] see Section 9.3.5) or calculations in GIS software. Project proponents may also use dated aerial photographs or accurate hand-drawn maps accompanied by records of where and when land parcels burned.
Soil organic carbon (SOC)	Required	Initial soil carbon stocks must be measured to the desired depth following Section 8.3.3 for both Modeled and Measured approaches. Where the Modeled Approach is used: 1) the chosen depth must match that applicable to the chosen soil carbon model. 2) initial soil carbon stocks must be measured because model predictions must be reassessed against measured changes in

[2] Required for Tier 2 methods of calculating methane emissions per the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*

[3] Available at: https://modis.gsfc.nasa.gov/data/dataprod/mod45.php

Baseline Scenario Indicator	Data collection	Methods
		SOC due to the project activity 5–10 years after the project start and every 5–10 years thereafter. 3) predictions of baseline soil carbon stocks or stock changes from the chosen model of soil carbon dynamics, such as Century (Ogle et al. 2010; Paustian et al. 1992; Piñeiro et al. 2006) or SNAPGRAZE (Ritchie 2020), must be assessed against baseline sampling data to demonstrate that the model is appropriate for use in the project area and can predict measured soil carbon stocks or stock changes from the project area.
Aboveground biomass: fuels	Required	Emissions from biomass burning depend on combustion factors of the proportion of the total aboveground biomass (tree, woody shrub plus sapling, and herbaceous) consumed by fire. These different biomasses may be treated as different fuel classes.[4] While aboveground herbaceous biomass is not tracked for removals because it typically turns over annually due to fire, decomposition, or consumption by detritivores (e.g., termites), it is an important metric for determining emissions from biomass burning. Aboveground herbaceous biomass (AGHB) in the baseline can be measured by standard clipping of multiple quadrats and drying and weighing both litter and green (live material).[5] Project proponents must estimate combustion factors for biomass of different fuel classes (where differentiated). After fire, project proponents must measure biomass in unburned, early burned, and late burned sampling plots, sorted by fuel classes where used. Where the woody plant fuel class is used and project proponents intend to claim increases in aboveground woody biomass carbon, the reduction in biomass burning emissions are subsumed in the increase in aboveground woody biomass carbon. Project proponents may quantify aboveground biomass using remotely sensed information that estimates biomass from reflectance data. Available satellite data include NDVI in high resolution (10 m or finer) imagery, and LiDAR (Dube et al. 2016; Issa et al. 2020; Muumbe et al. 2021; Zimbres et al. 2020). These must be calibrated to ground-based measurements with sufficient accuracy to detect differences in biomass between no burn, early burn, and late burn biomass with 95% confidence. The baseline calibration of a remote sensing method must have root mean square error (RMSE) of <30%.

[4] Examples of fuel classes are found in the Australian Government Savanna Fire Management methods, available at https://shorturl.at/WHZ8I

[5] Mohanbabu, N. and Ritchie, M.E. 2022. Large herbivore impact on plant biomass along multiple resource gradients in the Serengeti. Journal of Ecology DOI: 10.1111/1365-2745.13889.

Baseline Scenario Indicator	Data collection	Methods
		RMSE is a measure of how well model predictions agree with observed data and is calculated as follows: $$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(X_{p,i} - X_{o,i}\right)^2}{n}}$$ Where: $X_{p,i}$ = model-predicted value of a quantity (in this case SOC or a change in SOC) $X_{o,i}$ = observed quantity for comparison n = number of comparisons
Aboveground woody biomass: trees	Required/ Optional	Where project activities involve changes in fire management, aboveground woody biomass must be monitored. Where the decision tree in Figure 1 results in aboveground woody biomass being accounted for towards removals, baseline aboveground woody biomass must be measured at baseline control sites. Where project activities do not involve changes in fire management, quantification and monitoring of aboveground woody biomass stock changes is optional.

Proponents of projects with improved grazing practices as a project activity must demonstrate a grazing history, determined from past grazing plans, livestock grazing animal counts, ground measurements of grazing impacts, and/or interpretations of satellite imagery.

Even where fire is absent in the baseline scenario due to reductions in biomass fuel needed to propagate fire, it may become present in the project scenario due to improvements in grassland condition.

Changes in emissions and carbon stocks associated with project activities are compared with changes that occurred prior to the project start and changes that would have occurred in the baseline scenario. Due to high inter-annual variability, changes are compared with average conditions across the baseline period.

Where a modeled approach is used, the baseline conditions serve as key inputs for calibrating and validating the chosen model.

Projects must reassess their baseline following the selected quantification approach.

7 ADDITIONALITY

Project proponents must demonstrate regulatory surplus, and conduct a barrier analysis and/or investment analysis and a common practice analysis.

7.1 Regulatory Surplus

Project proponents must demonstrate regulatory surplus in accordance with the rules and requirements set out in the most recent versions of the *VCS Standard* and *VCS Methodology Requirements*. Where the project proponent demonstrates regulatory surplus, proceed to Section 7.2. Otherwise, the project activity is not additional.

7.2 Barrier analysis and/or investment analysis

Project proponents must follow the procedures and requirements of the most recent version of VCS tool *VT0008 Additionality Assessment* to conduct either a barrier analysis (Step 2) or an investment analysis (Step 3). Project proponents may choose to apply both analyses to further strengthen the additionality demonstration.

When applying a barrier analysis, barriers are limited to:

a) financial barriers

b) lack of awareness of financial and non-financial benefits for final users

c) low acceptance of new or alternative practices, services, or products associated with the project activity due to lack of knowledge

d) lack of equipment and/or infrastructure for implementation of the technology (e.g., livestock control collars, fire management equipment)

e) degraded soil that cannot support animal grazers

f) demographic pressure on the land (e.g., increased demand on land and competition for grazing resources) due to population growth or degradation of surrounding lands

g) social conflict among interest groups in the region where the project takes place

h) lack of organization of local communities

i) communal land ownership with a hierarchy of rights for different stakeholders that limits incentives to undertake the project activity

j) lack of suitable land tenure legislation and regulation to support the security of tenure

k) absence of clearly defined and regulated property rights in relation to natural resource products and services

l) other barriers as identified and justified by the project proponent for the proposed project area

Note — Projects may choose to demonstrate additional implementation barriers using the list of barriers provided in the most recent version of the VT0008 Additionality Assessment. *However, as a minimum requirement, project proponents must demonstrate additionality through the existence of at least one of the barriers listed above or an investment analysis. Other barriers may further strengthen the additionality demonstration but are not sufficient on their own.*

Where the project proponent demonstrates that all conditions of either the barrier analysis and/or the investment analysis per VT0008 are met, proceed to Section 7.2.2 (common practice analysis). Otherwise, the project activity is not additional.

7.2.1 Common practice analysis

Project proponents must conduct a common practice analysis in accordance with "Step 4c: Common Practice Analysis for Measures Not Listed in Step 4a" of the most recent version of *VT0008*. Where the project proponent demonstrates that the project is not considered common practice, the project is additional. Otherwise, the project activity is not additional.

8 QUANTIFICATION OF REDUCTIONS AND REMOVALS

8.1 Summary

The approaches for quantifying CO_2, CH_4, and N_2O emissions are listed in Table 5.

Table 5. Summary of allowable quantification approaches

GHG	Source/pool	Modeled approach[a]	Measured approach	Default factors
CO_2	SOC	X	X	
	Fossil fuel			X
	Aboveground woody biomass[b]		X	
CH_4	Dung decomposition			X

	Enteric fermentation			X
	Biomass burning			X
N_2O	Dung decomposition			X
	Biomass burning			X

[a] May only be used where a valid model is available (see model requirements in Appendix 3).

[b] Where woody biomass is harvested, project proponents must calculate the long-term average GHG benefit following guidance in the most recent versions of the *VCS Methodology Requirements*,[6] and the *VCS Standard*.[7]

Modeled Approach

An acceptable model is used to estimate GHG flux based on soil characteristics, grazing pressure, initial SOC stocks, and climatic conditions. Measurements of SOC stocks are required every five years or more frequently and are used to re-estimate model prediction error and recalibrate the model (i.e., "true-up", see Section 8.3.3).

Measured Approach

Direct measurement may be used to quantify changes in SOC and woody biomass carbon stocks. The baseline scenario is measured and remeasured directly at baseline control sites.

The use *VT0014 Estimating Organic Carbon Stocks Using Digital Soil Mapping*, is allowed with the measured approach (i.e., *VT0014* shall not be used when project apply the modeled approach).

Default factors

Baseline and project emissions are calculated using applicable default values and any monitored parameters. The most accurate emission factor applicable to the project conditions must be used, listed below in descending order of preference. Project proponents must use project-specific emission factors where available:

1) Project-specific emission factor from a peer-reviewed scientific publication
2) Alternative sources of information (e.g., government databases, industry publications) for establishing the default factor(s), with evidence provided that the alternative source of information is robust and credible (e.g., independent expert attestation)
3) Default factor derived using activity data collected during the project following guidance in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* to derive Tier 2 emission factors

[6] See Section 3.6.6 in the *VCS Methodology Requirements, v4.4*

[7] See Sections 3.2.28–3.2.30 of the *VCS Standard, v4.7*

4) Tier 1 and Tier 1a emission factor from the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, provided the project proponent justifies a lack of sufficient activity data and project-specific information sources

8.2 Soil Sampling

Measured Approach

Baseline SOC stocks and, where applicable, woody biomass carbon, are measured and remeasured directly at baseline control sites which are linked to sampling stations. Matching baseline control sites to sampling stations is based on biophysical and woody biomass similarity criteria (see Table 6).

Control sites must be within 250 km of their linked sampling stations. One control site may be linked to more than one sampling station provided the control site meets the similarity criteria for each sampling station to which it is linked.

Baseline SOC and, where applicable, woody biomass carbon stocks must be reported for the baseline control sites and for each sampling station within the project area.

A control site must be removed from the project where, at any point during the crediting period, it becomes subject to:

1) a natural disturbance that the linked sampling station does not experience.
2) management activities that are not in line with baseline practices.
3) similar alterations that make it no longer a valid control.

Where no other control sites remain that are linked with the associated sampling station, the sampling station must also be removed from the project. Project proponents are encouraged to include more control sites than the minimum required, to protect against the possibility of losing a sampling station.

Table 6. Similarity criteria for linking baseline control sites to sampling stations under the measured approach

Control Site Similarity Criteria	Threshold[a]
Biophysical Similarity Criteria	
Topography	Most frequent slope class by area must be the same in the sampling stations and control sites (to be determined from a slope map or GIS slope analysis (see Appendix 6).

Control Site Similarity Criteria	Threshold[a]
Soil texture to depth of project boundary (minimum 30 cm)	Most frequent soil texture class by area in the control site must be in the same FAO[8] soil textural class as the most frequent soil texture class by area in the linked sampling station.
Average SOC percent by dry weight to depth of project boundary (minimum 30 cm)	The percentage must not be significantly different from the area-weighted mean percentage SOC of the linked sampling station at a 90% confidence level.
Historical land cover[b]	Where the baseline scenario land use includes croplands, shrublands, woodlands, or degraded land, the baseline control site may include the same land use conversion. Conversion of the baseline control site must have occurred within ±10 years of the median year of conversion across all or an unbiased, representative sample of sampling stations.
Native vegetation	The site must be within the same terrestrial ecoregion[9] as the linked sampling station or the predominant ecoregion where the sampling station spans multiple ecoregions.
Climate zone	The site must be within the same IPCC-defined climate zone as the linked sampling station or the predominant climate zone where the sampling station spans multiple climate zones.
Precipitation[c]	The site's mean annual precipitation must be within ±100 mm of that of the linked sampling station
Woody Biomass Similarity Criteria (where applicable)	
Pre-existing woody biomass	The average basal area of woody stems >12.5 cm in diameter at breast height (DBH) in the control site must be within ±20% of the average basal area of woody stems >12.5 cm DBH at the linked sampling station.
Advanced regeneration	The average density of woody stems 2.5–12.5 cm DBH at the control site must be within ±20% of the average density of woody stems 2.5–12.5 cm DBH in the linked sampling station. Trees within a 20m radius of the sample point are sampled.
Proximal seed sources	In the direction of prevailing winds, the distance from the centroid of the control site to the closest existing tree line must not exceed the average distance in the linked sampling station by more than 20%.

[a]Estimates of these quantitative thresholds in control sites and sampling stations must be derived from unbiased, representative sampling or from mapped datasets. 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).

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

[c]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)

[8] See the FAO *World Reference Base for Soil Resources 2014* available at: https://www.fao.org/3/i3794en/I3794en.pdf The USDA Soil Texture Calculator (available at: 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.

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

Soil carbon measurements in the project area, or nearby similar habitat under similar management, climate, and soils as the project area, may not be available prior to the project start date. Therefore, the baseline scenario for changes in carbon stocks and emissions may be inferred from indicators of prior loss of soil carbon or demonstration of vegetation states different from those achievable as a result of the project activity (Table 7).

Table 7. Indicators of baseline emissions and/or carbon stock change

Baseline emission or carbon stock change Indicator	Data collection	Methods
Grazing intensity	Optional	Comparison of forage biomass inside and outside fenced exclosures (McNaughton 1985; Ritchie 2014) or inside and outside unfenced areas otherwise avoided by livestock, such as conservation areas, with similar soil and climate, or before and after planned grazing events
Ground measurements of vegetation quality and composition	Optional (one or more method required)	Field data on vegetation composition (biomass, percent cover, incidence). Dominant vegetation types that are associated with lower soil carbon (e.g., annual plants) or with grasses with high lignin and cellulose content such as *Pennisetum* spp. (Africa), *Spinifex* spp. (Australia), switchgrass *Panicum virgatum* or Johnson grass *Sorghum halepense* (North America), or *Paspalum* spp. (South America) following consumption by livestock. These data may be presented as visually estimated percentage cover of different vegetation types. Average percentage cover of annual and perennial grasses, bare ground, and shrubs must be provided where applicable. Photographic evidence of vegetative cover types and dominant plant taxa must be provided.
Grazing intensity	Optional (one or more method required)	Project proponents may estimate the average forage removal or grazing intensity (%) by all animals as measured from exclosure (fence) experiments, visual estimates calibrated from exclosure experiments, or ungrazed areas within the project area with similar soils and rainfall to areas where soil carbon is expected to increase
Photographic measurements of vegetation quality and composition	Optional (one or more method required)	GPS-referenced, dated photographs of a representative sample of the project area that can be used to judge a shift to project scenario vegetation from similar photographs taken of the same view at the same GPS point

Baseline emission or carbon stock change Indicator	Data collection	Methods
Remote measurements of vegetation quality and composition	Optional (one or more method required)	Estimates of grazing intensity over large areas may be made by using interpreted satellite images, such as indices of NDVI (Liu et al. 2007; Ren et al. 2011) or maps of burned areas (De Santis et al. 2010; Dempewolf et al. 2007) across at least five years, coupled with ground vegetation data to support the conclusion that images are correctly interpreted with reasonable accuracy (i.e., $R^2 > 0.35$ between index and vegetation measure from ground measurement).

Modeled Approach

In addition to one or more of the indicators found in Table 7, a modeled approach must demonstrate parameter values or model inputs that applied during the baseline period. Such values are used for model assessment and validation for the project area (seeTable 8). Parameters depend on the model used but may include livestock (or grazing animal) density, number of pastures used by livestock during the plant growing season, and fire frequency.

Table 8. Indicators of baseline emissions and/or removals – model parameters and inputs

Baseline emission or carbon stock change indicator	Data collection	Methods
Grazing animal density	Required where parameter is included in model	Numbers of animals recorded in: 1) randomized household surveys of at least 3% of households during the year prior to the project 2) researcher, government, or project proponent animal (e.g., wildlife) or livestock surveys 3) estimates in the project area or from similar habitats, climate, and soils provided in peer-reviewed literature. This information is required for estimating enteric methane emissions.

Baseline emission or carbon stock change indicator	Data collection	Methods
Number of grazing areas, pastures, paddocks, or blocks used per growing season	Required where parameter is included in model	Determined from: 1) narratives of local leaders, herders, conservation staff in focus groups 2) prior grazing plans or written descriptions of grazing animal activities 3) use of the project area by grazing animals prior to the project start date This information should lead to estimates of the number of different areas used by livestock during a plant growing season during the 10-year baseline period. Lack of management in the form of continuous livestock grazing or lack of grazing may also be considered a management activity.
Fire frequency	Required where parameter is included in model	Project proponents must demonstrate a fire history, as a map of areas that burned, the season of burning, and the number of times the areas burned over the ten-year baseline period. This may be obtained from satellite products, such as MODIS Burned Area Product[10] (as detailed in Section 9.3.5) that provide polygons of burned areas for 15-day periods throughout the dry or burning season or calculated in GIS software. Project proponents may also use dated aerial photographs or accurate hand-drawn maps accompanied by records of where and when land parcels burned.

8.2.1 Design and Establishment of Permanent Sampling Stations

Project proponents must establish permanent sampling stations with GPS locations recorded to 5-meter accuracy for both measured and modeled approaches. Measurements of carbon stocks in soil and wood (where relevant) at the same place may then be compared over time, controlling for initial differences in SOC, grazing and fire history, vegetation, topography, and other factors.

Project impacts on carbon stocks are best detected by measuring the change in carbon stocks between years at each sampling station and then averaging over all sampling stations rather than the difference between mean stocks across all sampling stations between years. This sampling approach greatly reduces the variance, and therefore, uncertainty, in changes in stocks between baseline and project activities and facilitates the use of a smaller number of

[10] http://modis.gsfc.nasa.gov/)

sampling points. Further details about measurements at these permanent stations are discussed in Sections 8.3.3 and 8.3.4.

Sampling stations must be distributed to achieve representation of the project area and/or designated strata within the project area. This may be achieved by random placement across the project area (random sample) or within project strata (stratified random sample). Alternatively, stations may be distributed uniformly (in a grid) across the project area or within strata. Project proponents using a modeled approach should consider additional sampling stations to increase the range of SOC values used to validate the chosen model (see Section 8.2.3).

8.2.2 Number of Sampling Stations

The total number of sampling stations, *n*, for the project area must be determined by using Equation (1), which assumes that the total area sampled for carbon is less than 5% of the project area or stratum.

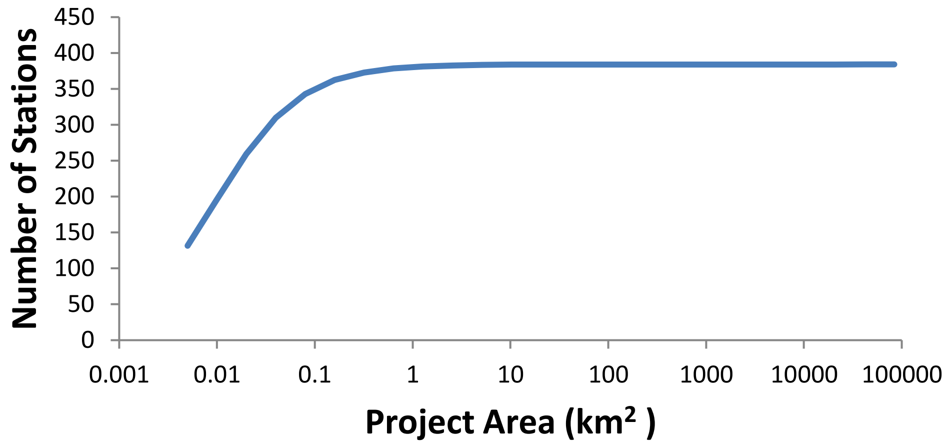
$$n_p = \left(\frac{t_{VAL}}{E}\right)^2 \times \left(\sum_i w_i \times s_{p,i}\right)^2 \tag{1}$$

Where:

n_p	=	Number of permanent sampling stations required to estimate difference in carbon stock at each station over *Y* years of a reassessment period
t_{VAL}	=	Two-sided pairwise Student's t-value at infinite degrees of freedom for the test of whether the change in carbon stock over *Y* years is different from zero
E	=	Acceptable margin of error (i.e., one-half the confidence interval) in estimating mean change in carbon stock within the project boundary (t d.m. or t d.m./ha)
w_i	=	Relative weight of stratum *i* (i.e., the proportion of the project area composed of stratum *i*) (dimensionless)
$s_{p,i}$	=	Standard deviation of difference in carbon stock over *Y* years of the re-assessment period at each sample point (t d.m. or t d.m./ha)

Project proponents must describe the sample type (i.e., individual, composite) and justify the choices in terms of uncertainty and project feasibility. The total number of sampling stations when using composite samples in the measured approach is largely insensitive to the total area of the project, as shown in Figure 2.

Figure 2. Estimated number of sampling stations needed to detect mean SOC increase of 0.3% over any time period for samples with a hypothetical standard deviation of 0.3% (100% of mean) and target standard error of less than 10%



8.2.3 Stratification

The project area must be stratified to obtain estimates of changes in carbon stocks that are representative of the respective strata, unless the project proponent demonstrates that stratification does not reduce overall uncertainty. Appendix 2 discusses an example in which stratification might not be appropriate.

Measured Approach

Stratification may be based on vegetation and management practices, topography (top, middle, and bottom of slopes), and soil texture (proportion of sand, silt, and clay) amongst others. Recommended approaches for stratification can be found in Goidts et al. (2009) and McNab et al. (1999).

All strata must be delineated with geodetic polygons. Further recommendations can be found in the most recent version of the *VM0042 Soil Sampling and Analysis (SSA) Handbook*.

Modeled Approach

For projects using a modeled approach, the chosen carbon dynamic model must be able to predict carbon stocks or changes in carbon stocks at each of a large number of sampling stations that differ in key factors, such as climate, soil type, past management, and vegetation. Additional sampling stations may be required to include enough variability in these factors to test that the model is appropriate for use in the project area.

Project proponents may compare errors (confidence intervals, standard errors, or uncertainty) between stratified and unstratified estimates to assess whether stratification decreases uncertainty in carbon stock change estimates, following steps in Appendix 2.

8.3 Baseline Emissions

Baseline emissions are calculated as follows:

$$BE_y = BEM_y + BEBB_y \quad (2)$$

Where:

BE_y = Baseline emissions in year *y* (t CO_2e)

BEM_y = Average annual baseline emissions from enteric methane in year *y* of the baseline period (t CO_2e)

$BEBB_y$ = Average annual baseline emissions from biomass burning in year *y* of the baseline period (t CO_2e)

Carbon stock changes in the baseline scenario are quantified as follows:

$$\Delta BCS_y = \Delta SOC_{BL,y} + \Delta AWB_{BL,y} \quad (3)$$

Where:

ΔBCS_y = Baseline carbon stock change in the project area in year *y* (t CO_2e)

$\Delta SOC_{BL,y}$ = Soil organic carbon stock change in the project area in the baseline scenario in year *y* (t CO_2e)

$\Delta AWB_{BL,y}$ = Aboveground woody biomass stock change in the project area in the baseline scenario in year *y* (t CO_2e)

8.3.1 Baseline Enteric Methane Emissions (BEM_y)

Domestic livestock grazing are classified as one of four animal types:

- ruminants (e.g. sheep, goats, cattle, buffalo) and camelids (e.g., camels, alpacas, guanacos, llamas)
- equids (e.g., donkeys, horses)
- pigs
- marsupials (wallabies and kangaroos)

Baseline methane emissions from grazing animals must be estimated from data on total numbers for different livestock categories *c* that reflect different species, age, sex, and body weight combinations, using Equation (4).

$$BEM_y = \sum_{c=1}^{K} \left(BN_c \times DMEF(W_c) \right) \times GWP_{CH_4} \times 365 \times 6.26 \times 10^{-7} \quad (4)$$

Where:

BEM_y = Average annual baseline emissions from enteric methane in year *y* of the baseline period (t CO2e)

BN_c	=	Baseline number of animals in category *c* (head)
$DMEF(W_c)$	=	Daily emission factor as a function of animal weight for category *c* (CH_4/day)
W_c	=	Average body weight during the baseline period for animals of category *c* (kg)
GWP_{CH4}	=	Global warming potential for methane (t CO_2e/t CH_4)
c	=	Category of grazing animals
K	=	Total number of categories of grazing animals (i.e., of different species, gender, age combinations)
365	=	Conversion factor for days to years
6.26×10^{-7}	=	Conversion factor for L CH_4/day to t CH_4/day

Daily enteric methane emissions may be determined using the allometric equations in Table 9.

Table 9. Allometric equations, with uncertainty, for daily methane emissions per animal for ruminants and camelids, equids, and pigs (Franz et al. 2010)

Animal type	*DMEF* (t CO_2e/day/	*N*	*R^2	Uncertainty Percent
Ruminants and camelids	$0.66 \times W_c^{0.97}$	62	0.88	9.5%
Equids	$0.18 \times W_c^{0.97}$	23	0.76	28.2%
Pigs	$0.07 \times W_c^{0.99}$	12	0.93	18.6%

Forage quality and fiber content affect methane emissions (Archimède et al. 2011) but are not considered in Equation (4) because they are difficult to measure across large-scale projects and would introduce additional uncertainty.

Depending on the relative abundance of equids in the grazing animal categories, uncertainty in methane emissions may induce an uncertainty deduction in the calculation of methane emission reductions.

8.3.2 Baseline Emissions from Biomass Burning (*BEBB*)

Baseline emissions from burning of aboveground biomass ($BEBB_y$) is estimated as follows:

$$BEBB_y = BEBB_{CH4,y} + BEBB_{N2O,y} \tag{5}$$

Where:

$BEBB_y$	=	Average annual baseline emissions from biomass burning during the baseline period (t CO_2e)
$BEBB_{CH4,y}$	=	Average annual baseline methane emissions from biomass burning during the baseline period (t CO_2e)
$BEBB_{N2O,y}$	=	Average annual baseline nitrous oxide emissions from biomass burning during the baseline period (t CO_2e)

Carbon dioxide emissions from herbaceous biomass are excluded because annual herbaceous production is assumed to decompose within one to two years and thus losses to burning equal the amount that would otherwise be lost to decomposition. Although values of methane and nitrous oxide emissions, $BEBB_{CH4,y}$ and $BEBB_{N2O,y}$ apply for a given year, and are thus annual for the baseline, these values should reflect average annual measurements over the ten years prior to the project start.

8.3.2.1 Baseline Emissions from Change in Aboveground Woody Biomass from Burning

Fire and grazing are likely to be the main drivers of change in aboveground woody biomass. Activities to sequester carbon may entail an increase in fire frequency that will reduce aboveground woody biomass but lead to an increase in soil carbon sequestration sufficient to increase total carbon stocks (Neary et al. 1999). Project proponents must account for carbon stock losses from the initial combustion of woody biomass in the quantification of baseline carbon stock changes.

Where a reduction in fire frequency is a project activity and woody plant carbon stocks are expected to increase, reversals of past and ongoing losses of woody plant biomass may be conservatively excluded (i.e., $\Delta AWB_{BL,y} = 0$).

8.3.2.2 Baseline Methane Emissions from Biomass Burning

Emissions from biomass burning depend on many factors (e.g., habitat, soil, timing of fire, climate). Project proponents may choose to subdivide the project area into more strata (time, habitat) than are used for estimating carbon stocks. The number of strata used for biomass burning measurements (*f*) must be equal to or greater than the number of strata for estimating carbon stocks (*s*).

Methane emissions from aboveground woody plant biomass burning must be accounted for because they would largely not occur during decomposition.

$$BEBB_{CH4} = \sum_{m=1}^{f} \frac{\sum_{b=1}^{b_m} BM_{b,m} \times CF_{b,m} \times EF_{CH4,b,m}}{10^3} \times PA_m \times GWP_{CH4} \qquad (6)$$

Where:

$BEBB_{CH4}$	=	Baseline methane emissions from biomass burning in the project area (t CO_2e)
$BM_{b,m}$	=	Baseline pre-fire biomass of fuel class *b* in stratum *m* (kg/ha)
$CF_{b,m}$	=	Combustion factor for fuel class *b* in stratum *m* (mean proportion of biomass burned)
$EF_{CH4,b,m}$	=	Emission factor for methane for fuel class *b* in stratum *m* (g CH_4/kg biomass burned)
PA_m	=	Area of stratum *m* (ha)
GWP_{CH4}	=	Global warming potential of CH_4 (t CO_2e /t CH_4)
10^3	=	Conversion factor for kilograms to tonnes

m	=	1, 2, …, f burning stratum
b	=	1, 2, …, b_m fuel class

Fuel classes (b) must be specified for validation and should include at least herbaceous, fine woody, and coarse woody classes. Project proponents may include additional fuel classes where relevant.

The combustion factor ($CF_{b,m}$) has two components: the proportion of biomass consumed per unit area and the proportion of area burned in stratum m.

$$CF_{b,m} = \frac{MBA_m}{PA_m} \times \left(1 - \frac{BMAF_{b,m}}{BM_{b,m}}\right) \quad (7)$$

Where:

$CF_{b,m}$	=	Combustion factor for fuel class b in stratum m (mean proportion of biomass burned)
MBA_m	=	Mean area burned in stratum m over the 10 years prior to project start (ha)
PA_m	=	Stratum area (ha)
$BMAF_{b,m}$	=	Biomass of fuel class b after fire in stratum m (kg/ha)
$BM_{b,m}$	=	Baseline pre-fire biomass of fuel class b in stratum m (kg/ha)

Burned area over the ten years prior to the project start may be estimated (e.g., using MODIS data) and biomass of different fuel classes before and after fire determined at the project start (y = 0).

8.3.2.3 Nitrous Oxide Emissions from Biomass Burning

Nitrous oxide emissions from biomass burning must be accounted for because they would largely not occur during decomposition.

$$BEBB_{N2O} = \sum_{m=1}^{f} \frac{GWP_{N_2O} \times \sum_{b=1}^{b_m}\left(BM_{b,m} \times CF_{b,m} \times EF_{N_2O,b,m}\right)}{10^3} \times PA_m \quad (8)$$

Where:

$BEBB_{N2O}$	=	Baseline nitrous oxide emissions from biomass burning in the project area ($t\ CO_2e$)
$BM_{b,m}$	=	Baseline pre-fire biomass of fuel class b in stratum m (kg/ha)
$CF_{b,m}$	=	Combustion factor for fuel class b in stratum m (mean proportion of biomass burned)
$EF_{N2O,b,m}$	=	Emission factor for nitrous oxide for fuel class b in stratum m (g N_2O/kg biomass burned)
GWP_{N2O}	=	Global warming potential of nitrous oxide (t CO_2e /t N_2O)
$PA_{m.}$	=	Area of stratum m (ha)

10^3	=	Conversion factor for kilograms to tonnes
m	=	1, 2, …, f burning stratum
b	=	1, 2, …, b_m fuel class

8.3.3 Baseline Soil Organic Carbon Stock

Changes in soil organic carbon stocks must be estimated for the baseline scenario. Estimates may be measured or modeled.

Where soil carbon stocks increase in the baseline scenario, project proponents must assess the expected change in soil carbon under the baseline scenario and account for it in the removals calculation.

Whether the Measured or Modeled Approach is applied, initial $SOC_{m,j,0}$ must be measured at each sampling station j in stratum m in year 0. Project proponents must use the equivalent soil mass (ESM) method unless they demonstrate that the project activity will not cause changes in bulk density, in which case a soil volume (SV) method may be used.

For both ESM and SV, project proponents must measure the following:

- Soil core depth in stratum m at station j in year y = 0 ($DEPTH_{j,m,0}$): measured to at least 30 cm or down to hardpans or bedrock, and matching calculations from soil carbon models where the modeling approach is used.
- Percent SOC in stratum m at station j in year y = 0 ($SOC\%_{j,m,0}$): measured in a professional laboratory using the Walkley-Black method[7] (Walkley and Black 1934), combustion methods (Brye and Slaton 2003), or multi-spectral diffraction with an infra-red spectrometer following calibrations specific to the project area (Knadel et al. 2011). Spectrometers may be laboratory-based or where criteria in Appendix 5 are met, in-situ special probes may be inserted directly in the soil.[11]
- Bulk density at station j in stratum m in year y = 0 ($BULK_{j,m,0}$): measured in Mg dry soil/m^3, which is equivalent to g/cm^3, the unit most commonly reported by laboratory analyses

Some methods measure soil carbon density ($SOC\%_{j,m,0} \times BULK_{j,m,0}$) simultaneously (e.g., Gyawali et al. 2025) and may be used where they satisfy criteria detailed in Appendix 5 and the project proponent states that the method measures the product of the two parameters.

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[7] https://www.fao.org/3/ca7471en/ca7471en.pdf

[11] For example using equipment manufactured by Yard Stick, available at: https://www.useyardstick.com/

ESM method

At time *y*, project proponents must measure *SOC%* and *BULK* of at least two depth intervals *d* down to a maximum depth ($DEPTH_{max}$). These estimates are used to calculate a soil carbon density versus soil mass relationship for the entire soil core using Equations (9)–(14).

$$\boldsymbol{MASS_{d,j,m,y} = \pi \times RADIUS^2 \times BULK_{d,j,m,y} \times \frac{DEPTH_{max}}{k}} \tag{9}$$

Where:

$MASS_{d,j,m,y}$	=	Mass of soil at depth *d* at sampling station *j* in stratum *m* in year *y*
RADIUS	=	Radius of the soil core
$BULK_{d,j,m,y}$	=	Bulk density at depth *d* at sampling station *j* in stratum *m* in year *y*
d	=	1, 2, …, *k* depth interval
$DEPTH_{max}$	=	Maximum depth sampled

Project proponents must then calculate cumulative SOC density and soil mass across *d* soil depth layers for *d* = 1, 2, …, *k* as follows:

$$SOC_{j,m,0} = \sum_{d=1}^{c} MASS_{d,j,m,y} \times SOC\%_{d,j,m,y} \tag{10}$$

$$MASS_{j,m,0} = \sum_{d=1}^{c} MASS_{d,j,m,y}$$

Typically, $SOC\%_{d,j,m,y}$ declines with increasing depth, so a linear regression, assuming an intercept of (0, 0) of the logarithm of $SOC_{c,j,m,y}$ versus $MASS_{m,j,y,c}$ for the cumulative depth classes yields a relationship between cumulative *SOC* and *MASS* in year *y* at station *j* in stratum *m.*

Typically, the selected value of *MASS* = $MASS_{d,m,j,y}$ where *d* corresponds to the depth layer at which SOC change is reported (or corresponds to a desired modeling depth)

$$d = \frac{k \times DEPTH_{desired}}{DEPTH_{max}} \tag{11}$$

Where:

d	=	1, 2, …, *k* depth interval
k	=	Number of depth intervals
$DEPTH_{desired}$	=	Desired depth for reporting or correspondence to a SOC dynamic model
$DEPTH_{max}$	=	Maximum depth sampled

SV method

$SOC_{m,j,0}$ may be calculated from multiple pooled soil cores from each station as:

$$SOC_{j,m,0} = DEPTH_{j,m,0} \times SOC\%_{j,m,0} \times BULK_{j,m,0} \qquad (12)$$

Where:

$SOC_{j,m,0}$	=	SOC density in station *j* in stratum *m* in year *y* =*0* (t C/ha)
$DEPTH_{j,m,0}$	=	Soil core depth at station *j* in stratum *m* in year *y* = *0* (i.e., at the start of the project or since the last verification)
$SOC\%_{j,m,0}$	=	Percent SOC in dry soil from the entire soil profile to the chosen depth at station *j* in stratum *m* in year *y* =*0*
$BULK_{j,m,0}$	=	Bulk density at sampling station *j* in stratum *m* in year *y*=*0*

Note that $SOC\%_{m,j,0}$ is a percent (0-100) and allows the equation to correctly calculate SOC density (tons/ha) without further calibration.

$BULK_{m,j,0}$ must be measured in the field by sampling a known volume of soil, sieving rocks and subtracting their volume and then drying and weighing the remaining soil. Bulk density accounts for whether soil is loosely or densely packed and must not include volume occupied by rock fragments or pebbles (which is measured and subtracted from the total volume of the sample).

Soil sampling must include the following features:

1) Soil sampling must follow established best practices, such as those found in FAO (2019, 2020) and Soil Science Division Staff (2017) or a source of equivalent reliability.

2) All organic material (e.g., living plants, crop residue) must be cleared from the soil surface before soil sampling.

3) SOC content and soil mass must 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 fully homogenized prior to subsampling

4) Soil mass must not include particles greater than 2mm in diameter (i.e., gravel/stones) nor plant material

For further details on operational guidance to implement these best practices, projects are recommended to use the latest version fo the VM0042 Soil Sampling and Analysis (SSA) Handbook.

Measured Approach

The baseline SOC stock change measured in control plots at station *j* in stratum *m* through year y (tC/ha) is calculated as follows:

$$\Delta SOC_{BL,j,m,y} = SOC_{BL,j,m,y} - SOC_{BL,j,m,0} \qquad (13)$$

Where:

$\Delta SOC_{BL,j,m,y}$	=	Baseline SOC stock change at station j in stratum m through year y (tC)
$SOC_{BL,j,m,y}$	=	SOC stock at station j in stratum m through year y (tC)
$SOC_{BL,j,m,0}$	=	SOC stock at station j in stratum m in year y=0 (tC)

The baseline SOC stock change through year y is calculated as follows:

$$\Delta SOC_{BL,y} = \frac{44}{12} \times \sum_{m,j} \Delta SOC_{BL,m,j,y} \quad (14)$$

Where:

$\Delta SOC_{BL,y}$	=	Baseline SOC stock change through year *y* (t CO_2e)
44/12	=	
$\Delta SOC_{BL,j,m,y}$	=	Baseline SOC stock change at station j in stratum m through year y (t C)

Modeled Approach

Projects applying a modeled approach must follow the following steps:

1) Set the initial SOC stock (y=0): Determined at project start via direct measurements at y = 0 or (back-) modeled to y = 0 from measurements collected within ±5 years of y = 0.
2) Gather all the biophysical model inputs that represent the baseline scenario, e.g., overgrazing.
3) Run the model for n years (where n>30) at validation and at every verification, with updated biophysical model inputs.
4) Where SOC stocks are decreasing in the baseline scenario, SOC stock at year = y must be set equal to SOC stock at year = 0 (i.e., initial SOC stock as per step1).
5) Where SOC stocks are increasing in the modeled baseline scenario, modeled values of SOC stock at year y must be used.
6) Perform a model true-up at least every five years

Under step 5 described above, the annual increment in SOC is determined by the difference in SOC between the SOC stock at y = 0 ($SOC_{m,j,0}$) and the modelled baseline SOC stock at equilibrium ($BSOC_{m,j,L}$) divided by the length of the project (L). The Baseline equilibrium must be determined assuming that baseline management practices are implemented.

$$\Delta SOC_{BL,y} = \frac{Y \times \sum_{m=1}^{s} \left(\frac{PA_m}{z_m} \times \sum_{j=1}^{z_m} \left(BMSOC_{j,L,m} - SOC_{j,m,0} \right) \right)}{L} \times \frac{44}{12} \quad (15)$$

Where:

$\Delta SOC_{BL,y}$	=	Baseline SOC stock change through year *y* (t CO_2e)
Y	=	number of years from y=0 to y
PA_m	=	Project area of stratum *m* (ha)
$BMSOC_{j,L,m}$	=	Baseline modeled equilibrium SOC stock at station *j* in stratum *m* at the end of the project lifetime year L, based on parameter values at station *j* or from across z_m sampling stations in stratum *m* (tC/ha)
$SOC_{j,m,0}$	=	SOC stock at station *j* in stratum *m* at year y=0 (tC/ha)
L	=	Years of project lifetime or years to reach equilibrium, whichever is less
44/12	=	Conversion factor from tC to tCO_2e

The model true-up referred to under Step 6 above involves using remeasurement data to re-estimate model prediction error and/or recalibrate the model in relation to measured SOC stocks. This ensures the model continues to accurately represent actual biogeochemical processes and does not overestimate removals. Projects must meet the following requirements associated with model true-up, listed in table 2 below.

Table 10. Model true-up requirements

Model true-up aspects	Associated requirements
Frequency of Remeasurement	• Direct remeasurement every 5 years under the Modeled Approach. • Measurements used for initial model setup (y=0) and future true-up. • More frequent remeasurement allowed, but only data ≥5 years apart must be used for model validation.
Sampling Methodology	• Remeasure SOC stocks at the same geographic locations as baseline (paired sampling) for accuracy.
Model Validation & Recalibration	• Initial model error based on peer-reviewed data, see for example section 5.2.3 of VMD0053. • Post-remeasurement, combine new and external data to expand calibration/validation dataset. • Repeat model validation procedures, see for example VMD0053. • Submit updated Model Validation Report (MVR) and update model prediction error and uncertainty. • The updated MVR and uncertainty calculations must be verified.
Outcomes	• Upon MVR approval, rerun model simulations from y=0 through current verification period.

Model true-up aspects	Associated requirements
	• Recalculate uncertainty deductions for SOC emission reductions/removals for current and future periods. • Previously issued Verified Carbon Units (VCUs) remain unchanged.

8.3.4 Baseline Woody Biomass Carbon Stock

Under the applicability condition that baseline emissions derived from livelihood-driven human impacts on aboveground woody biomass must be minimal and project activities cannot significantly alter such livelihood-driven activities, it is likely that fire and grazing are the main drivers of change in aboveground woody vegetation (though other drivers such as climate change or seasonal flooding that encourages (or discourages) natural regeneration and/or dieback should be considered). Additional drivers, such as climate change or flooding, etc. would be expected to drive a similar direction of change in woody biomass regardless of fire or grazing. Thus, differences in net removals to biomass between baseline (high fire) and project (low fire) conditions can therefore be attributed to project activities. Where a reduction in fire frequency is a project activity, woody plant carbon stocks are expected to increase as a consequence, and therefore past and/or ongoing losses of woody plant biomass may be conservatively excluded (i.e., $\Delta AWB_{BL,y}$ = 0).

In the case where aboveground woody carbon stocks are increasing in the baseline scenario, proponents should determine if project activities will decrease aboveground woody plant carbon stocks (Eq. 9). If past grazing pressure has been high enough to reduce fuel loads, past fire frequency may have been very low and woody plants, particularly shrubs, may have become abundant. If so, activities to sequester carbon may entail an increase in fire frequency that will reduce aboveground woody biomass but lead to an increase in soil carbon sequestration sufficient to increase total carbon stocks (Neary et al. 1999). If fire will be employed to reduce woody vegetation in the project scenario, the loss of aboveground woody biomass must be accounted for unless it can be shown to be de minimis relative to all other emissions and removals in the project scenario.

woody biomass carbon stocks must be estimated for time t = 0 (measured within ±2 years of time t=0) and remeasured over time in sample plots located in the baseline control sites to determine the cumulative biomass carbon stock change relative to t = 0 biomass carbon stocks over the crediting period. Measurements are done through standard forest inventory methods coupled with allometric conversions of tree size metrics (like diameter at breast height [dbh]) to total tree carbon mass, or by using calibrated new high resolution remote sensing methods such as LIDAR (Zhou et al. 2022).

Woody biomass carbon stocks in the baseline control sites through year y are calculated as:

$$AWB_{BL,y} = \frac{44}{12} \times \frac{WCD_m}{1000} \times \sum_{m=1}^{s} \frac{PA_m}{z_m} \times \sum_{j=1}^{zm} AWB_{BL,j,m,y} \quad (16)$$

Where:

$AWB_{BL,y}$	=	baseline aboveground woody biomass carbon through year y (t CO_2e)
44/12	=	conversion of t C to t CO_2e
WCD_m	=	Proportion of wood composed of carbon[12] (kg C/kg biomass)
1/1000	=	Conversion of kg/ha to metric tons/ha
PA_m	=	
z_m	=	number of sampling stations in stratum *m*
j	=	station index
m	=	Stratum index
s	=	Number of strata
$AWB_{BL,j,m,y}$	=	Aboveground woody biomass at baseline control site(s) for stratum *m* and station *j* through year y (kg/ha)

The variation of woody biomass carbon stocks in the baseline scenario is measured in the same way it is measured in the project scenario, i.e., by estimating the difference in carbon stocks at two points in time.

The cumulative change in woody biomass carbon stocks in baseline control sites, summed across each corresponding sampling station for year y*,* is quantified as:

$$\Delta AWB_{BL,y} = AWB_{BL,y} - AWB_{BL,0} \quad (17)$$

Where:

$\Delta AWB_{BL,y}$	=	Cumulative carbon stock change in aboveground woody biomass in the baseline control sites through year *t* (t CO_2e)
$AWB_{BL,y}$	=	Baseline aboveground woody biomass carbon through year y (t CO_2e)
$AWB_{BL,0}$	=	Baseline aboveground woody biomass carbon through year y=0 (t CO_2e)

8.4 Project Emissions

Project emissions and carbon stock changes depend on the principal set of project activities. Projects that manage grazing must account for changes relative to baseline methane emissions by grazing animals and changes in (WBC) and SOC. Projects that reduce fire frequency and/or intensity must account for expected increases in SOC and WBC or may optionally account for

[12] CDM, *A/R Methodological Tool: Estimation of carbon stocks and change in carbon stocks*

CDM, A/R Methodological Tool: Estimation of carbon stocks and change in carbon stocksof trees and shrubs in A/R CDM project activities, Version 2.1. 2011, UNFCCC Annex 13EB 60.

MacDicken, K.G., *A guide to monitoring carbon storage in forestry and agroforestry projects*. 1997, Winrock International reduction in methane and nitrous oxide emissions produced from biomass burning rather than increases in WBC. Projects that use fire events to remove unpalatable woody plants—usually shrubs—in order to stimulate grass and root production can increase SOC. These projects must account for increased methane and nitrous oxide emission from burning events and emissions from decreased WBC.

8.4.1 Project Enteric Methane Emissions (PEM_y)

When an animal population decline occurs in the project scenario, the project proponent must use the animal population in the baseline scenario to calculate with-project emissions to avoid crediting reductions resulting from animal 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).

However, whether or not methane emissions from livestock are reduced, calculations must be based on project data from animal counts or censuses and emission factor data based on project area-applicable body weight of each category from the equations in Table 7 and Equation 3 (Section 8.1.3.1).

$$PEM_y = \sum_{c=1}^{K} \left(PN_{c,y} \times DMEf\left(W_{c,y}\right)\right) \times GWP_{CH4} \times 365 \times 6.26 \times 10^{-7} \quad (18)$$

Where:

PEM_y	=	Project methane emissions from livestock in year y (t CO_2e)
$PN_{c,y}$	=	Project number of animals of each category c in year y (head)
$DMEf(W_{c,y})$	=	Daily emission factor as a function of animal weight in year y for category c (L CH_4 animal^{-1} · day^{-1}) (equations in Table 7)
$W_{c,y}$	=	Average body weight during year y for animals of category c (kg)
GWP_{CH4}	=	Global warming potential for methane (tCO_2e / tCH_4)
365	=	Conversion factor for days to a year
6.26×10^{-7}	=	Conversion factor for L CH_4 / day to metric tons CH_4 / day

Equation (18) is the same as Equation (4) (used for calculating baseline methane emissions) but with an important difference in time frame; the baseline emissions are a yearly average of the historical baseline period, while the project scenario is accounted for on a per year basis based on management records of animal species, number, and weight monitoring. The number of grazing animals must be re-measured during the project monitoring periods, because new animal categories result due to project activities (e.g., there is a shift to using different breeds or species of livestock).

8.4.2 Project Emissions From Biomass Burning (PEBBy)

Projects may account for reduced emissions from biomass burning by comparing project burning emissions of methane and nitrous oxide with baseline emissions. Where project activities increase fire frequency (e.g., to remove shrubs) and lead to a net increase in total carbon stocks, the project emissions from loss (or gain) in aboveground woody biomass, methane and nitrous oxide due to project activities to change the frequency and extent of burning of biomass, $PEBB_y$, t CO_2e, are calculated using the following equation:

$$PEBB_y = PEBB_{CH4,y} + PEBB_{N2O,y} \tag{19}$$

Where:

$PEBB_y$	=	
$PEBB_{CH4,y}$	=	Project emissions from methane emissions due to biomass burning in year *y* (t CO_2e)
$PEBB_{N2O,y}$	=	Project emissions of nitrous oxide due to biomass burning in year *y* (t CO_2e)

Note that emissions of CO2 from changes in herbaceous biomass are excluded because annual herbaceous production is assumed to decompose within a year and thus losses to burning simply compensate for losses to decomposition.

8.4.2.1 Project Methane Emissions from Biomass Burning.

Methane emissions from biomass burning must be accounted for because they would largely not occur during decomposition.

$$PEBB_{CH4,y} = \sum_{m=1}^{f} \frac{GWP_{CH_4} \times \sum_{b=1}^{b_m}\left(PBM_{b,m,y} \times PCF_{b,m,y} \times EF_{CH_4,b,m}\right)}{10^3} \times PA_m \tag{20}$$

Where:

$PEBB_{CH4,y}$	=	project emissions of methane from biomass burning on the project area in year *y* (t CO_2e)
GWP_{CH4}	=	global warming potential of CH_4 (t CO_2e /t CH_4)
$PBM_{b,m,y}$	=	project pre-fire biomass (kg/ha) of fuel class *b* in stratum *m* and year *y*.
$PCF_{b,m,y}$	=	project combustion factor for fuel class *b* in stratum *m* in year *y* (mean proportion of biomass burned). This can be changed by project activities, such as a shift from late season to early season burning, and thus is expected to be different under project activities and in different years
$EF_{CH4,b,m}$	=	emission factor for methane for fuel class b (g CH_4 / kg biomass burned) in stratum *m*
PA_m	=	area of stratum *m* (ha)
10^3	=	metric ton/kg
f	=	number of burning strata
m	=	stratum
b	=	1, 2, …, b_m fuel class

Fuel classes refer to different states of biomass, such as the herbaceous, fine woody, and coarse woody classes used in the Australia fire methodology [71]. Measurements of herbaceous biomass are reviewed in the parameter tables in sections 9.1 and 9.2. Fuel classes can be defined specifically to each project but must be identified at validation.

The project combustion factor in Equation (20) has two components: the proportion of biomass consumed per unit area and the proportion of area burned in burn stratum m.

$$PCF_{b,m,y} = \left(\frac{PBA_{m,y}}{PA_m}\right) \times \frac{PBMAF_{b,m,y}}{PBM_{b,m,y}} \qquad (21)$$

Where:

$PCF_{b,m,y}$	=	
$PBA_{m,y}$	=	area burned (ha) in burn stratum *m* during monitoring year *y*
PA_m	=	stratum area (ha)
$PBMAF_{b,m,y}$	=	project biomass of fuel class *b* in stratum *m* after fire in monitoring year *y* (kg/ha)
$PBM_{b,m,y}$	=	project biomass of fuel class *b* in stratum m before fire in monitoring year *y* (kg/ha)

8.4.2.2 Project Nitrous Oxide Emissions from Biomass Burning

Nitrous oxide emissions from biomass burning must be accounted for because these emissions would largely not occur during decomposition. Nitrous oxide emissions can be changed by project activities such as shifting the season of burning and changes in the proportion of fuel among fuel classes (e.g., more coarse woody fuel, less fine woody fuel) in addition to changes in the extent and frequency of fires and the combustion factor or proportion of biomass burned in burned areas.

$$PEBB_{N2O,y} = \sum_{m=1}^{f} \frac{GWP_{N_2O} \times \sum_{b=1}^{b_m}\left(PBM_{b,m,y} \times PCF_{b,m,y} \times EF_{N_2O,b,m}\right)}{10^3} \times PA_m \qquad (22)$$

Where:

$PEBB_{N2O,y}$	=	project emissions of N_2O from biomass burning on the project area in year *y* (t CO_2e)
GWP_{N2O}	=	global warming potential of N_2O (t CO_2e /t N_2O)
$PBM_{b,m,y}$	=	project pre-fire biomass (kg/ha) of fuel class *b* in stratum *m* in year *y*
$PCF_{b,m,y}$	=	project combustion factor for fuel class *b* in stratum *m* (mean proportion of biomass burned). This is calculated in Equation (22)
$EF_{N2O,b,m}$	=	emission factor for methane for fuel class *b* (g N_2O / kg biomass burned) in stratum *m*
PA_m	=	area of stratum *m* (ha)
10^3	=	conversion factor for kilograms to metric tons
f	=	number of burning strata
b	=	fuel class

Again, fuel class b refers to different states of biomass, such as, for example herbaceous, fine woody, and coarse woody classes. Fuel classes can be defined specifically for each project but must be identified at validation.

The emission factors for methane and nitrous oxide may be obtained from literature, either from global values or Tier 2 habitat specific values (Laris et al. 2021; Russell-Smith et al. 2021).

8.4.3 Project Woody Biomass Carbon Stock

Where project activities involve changes in fire management, the project proponent must monitor changes in aboveground woody biomass to quantify variations of aboveground woody plant carbon stocks. Where the project activities do not involve changes in fire management and are otherwise unlikely to change WB, the project proponent may exclude changes in the aboveground woody biomass carbon pool by assuming $PRWBC_y = 0$.

If project activities are expected to increase aboveground woody biomass through the increased recruitment of saplings and reduced mortality of existing trees, the increase in carbon stocks can be conservatively excluded.

Alternatively, the project can account for increases in aboveground woody carbon stocks.

Increases in aboveground woody carbon stocks due to project activities using a **measurement approach.** Project proponents must decide whether their activities will lead to an increase in WB and whether they wish to claim issuances based on increases in woody biomass.

Woody biomass carbon stocks in the project through year y are calculated as:

$$WB_{PR,y} = \frac{44}{12} \times \frac{WCD_m}{1000} \sum_{m=1}^{s} \frac{PA_m}{z_m} \sum_{j=1}^{zm} WB_{PR,j,m,y} \tag{23}$$

Where:

$WB_{PR,y}$	=	Project aboveground woody biomass carbon through year y (t CO_2e)
44/12	=	conversion of t C to t CO_2e
WCD_m	=	Proportion of wood composed of carbon[13] (kg C/kg biomass)
1/1000	=	conversion of kg/ha to metric tons/ha
PA_m	=	
z_m	=	number of sampling stations in stratum *m*

[13] CDM, *A/R Methodological Tool: Estimation of carbon stocks and change in carbon stocks*

CDM, A/R Methodological Tool: Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities, Version 2.1. 2011, UNFCCC Annex 13EB 60.

MacDicken, K.G., *A guide to monitoring carbon storage in forestry and agroforestry projects*. 1997, Winrock International

$WB_{PR,j,m,y}$	=	Aboveground woody biomass in the project area stratum *m* and station *j* through year y (kg/ha)
j	=	station index
m	=	stratum index

The cumulative change in project woody biomass carbon stocks, summed across each sampling station for year y, is quantified as:

$$\Delta AWB_{PR,y} = AWB_{PR,y} - AWB_{PR,0} \quad (24)$$

Where:

$\Delta AWB_{PR,y}$	=	Cumulative project carbon stock change in aboveground woody biomass through year *t* (t CO_2e)
$AWB_{PR,y}$	=	project aboveground woody biomass carbon through year y (t CO_2e)
$AWB_{BL,0}$	=	project aboveground woody biomass carbon through year y=0 (t CO_2e)

8.4.4 Project Soil Organic Carbon Stock Change

The determination of change from baseline equilibrium SOC density depends on the type of project approach used.

Measured Approach

Where the measured approach is applied, the project SOC stock change (in t CO_2e) is calculated using the following equation:

$$\Delta SOC_{PR,y} = \sum_{m=1}^{s}\left(\frac{PA_m}{z_m} \times \sum_{j=1}^{z_m}\left(SOC_{j,m,Y} - SOC_{j,m,0}\right)\right) \times \frac{44}{12} \quad (25)$$

Where:

$\Delta SOC_{PR,y}$	=	Project SOC stock change through year *y* (tCO_2e)
PA_m	=	Project area of stratum *m* (ha)
m	=	1, 2, …, s strata
z_m	=	Number of sampling stations in stratum *m*
$SOC_{j,m,Y}$	=	Project SOC measured at station *j* in stratum *m* in year *Y* at the end of the monitoring period (tC/ha)
$SOC_{j,m,0}$	=	SOC in station *j* in stratum *m* in year y=0 (tC)
44/12	=	Conversion factor from tC to tCO_2e

$$SOC_{j,m,y} = DEPTH_{j,m,y} \times SOC\%_{j,m,y} \times BULK_{j,m,y} \quad (26)$$

Where:

$SOC_{j,m,y}$	=	Project SOC measured at station *j* in stratum *m* in year *y* (tC/ha)
$DEPTH_{j,m,y}$	=	Soil core depth at station *j* in year *y* (cm)
$SOC\%_{j,m,y}$	=	Percent soil carbon at station *j* in stratum m in year *y*

$BULK_{j,m,y}$	=	Bulk density at station *j* in stratum *m* in year *y* (Mg dry soil/m^3; or equivalently, g dry soil/cm^3)

Note that this formula assumes that SOC in year *Y* and in year= *0* (baseline) or y>0 (since last verification) will be measured at a large number of sampling stations *j* in a stratified project area with *s* strata, including z_m stations in each stratum *m*.

Modeled Approach

The selected project area must use a validated soil carbon model to simulate the projected soil organic carbon (SOC) density at the end of the project lifetime. This value is called the project modeled SOC, denoted PMSOCm,j,L, where m corresponds to the sampling station, j corresponds to each stratum, and L refers to the project lifetime. The simulation is performed for each sampling station within each stratum, considering the expected project activities.. Expected grazing intensities and/or fire frequencies under project activities will combine in the model with other parameters as needed for the chosen soil carbon model to generate predicted soil carbon density at the end of the project lifetime $PSOC_{m,j,L}$ or year L for each sampling station, assuming that project activities will be implemented. The input parameters for the soil carbon model must be chosen to such that conservative estimates of carbon removals are generated. Uncertainties for each parameter in the model must be available to determine an overall uncertainty for $PSOC^{eq}_{m,j,L}$ with a Monte Carlo simulation (IPCC 2000a; Ogle et al. 2010) [43, 44], as discussed in detail in Section 8.6.3.

Carbon typically accrues in response to management changes with decreasing increments over time as equilibrium is approached (Paustian et al. 1992; Thornley and Cannell 1997; Williams et al. 1989). Thus conservatively, the annual increment in SOC is determined by the difference in SOC between the SOC stock at y = 0 ($SOC_{m,j,0}$) and the modelled project SOC stock at equilibrium ($PSOC_{m,j,L}$) divided by the length of the project (L). The project equilibrium must be determined assuming that project activities will be implemented.

Measurements of SOC stocks are required every five years or more frequently. The remeasurement data is used to re-estimate model prediction error and recalibrate the model (i.e., “true-up”, see Section X).

$$\Delta SOC_{PR,y} = \frac{Y \times \sum_{m=1}^{s}\left(\frac{PA_m}{z_m} \times \sum_{j=1}^{z_m}\left(PMSOC_{j,L,m} - SOC_{j,m,0}\right)\right)}{L} \times \frac{44}{12} \qquad (27)$$

Where:

$\Delta SOC_{PR,y}$	=	Project SOC stock change through year *y* (tCO_2e)
Y		number of years from y=o to y
PA_m	=	Project area of stratum *m* (ha)
z_m	=	

$PMSOC_{j,L,m}$	=	Project modeled equilibrium SOC stock at station *j* in stratum *m* at the end of the project lifetime year L, based on parameter values at station *j* or from across z_m sampling stations in stratum *m* (tC/ha)
$SOC_{j,m,0}$	=	SOC stock at station *j* in stratum *m* at year y=0 (tC/ha)
L	=	Years of project lifetime or years to reach equilibrium, whichever is less
44/12	=	Conversion factor from tC to tCO_2e

8.5 Leakage

In natural grasslands, the reduction in number of animals compared to pre-project scenario is source of leakage emissions, which must be assessed and accounted for using the latest version of *VMD0054 Module for Estimating Leakage from ARR Activities.* VMD0054 accounts for activity-shifting and market leakage due to the displacement of agricultural activities (including grazing). It was designed together with *VM0047 Afforestation, Reforestation and Revegetation*, however the leakage assessment fits any land-use project impacting agricultural production. Therefore, projects may disregard any mention within *VMD0054*, specifying the tool is specific to ARR activities or *VM0047*.

Additionally, project proponents must prevent or manage temporary excursions of livestock from inside to outside the project area, Where the project area is not fenced, such as in open pastoralist systems, the movement and excursion of livestock to more than two kilometers from the project area boundary is considered leakage[14]. Enteric methane emissions from temporary animal movements off the project area are deemed as zero because project methane emissions are accounted from project animals regardless of whether they are on or off the project area and movement of project livestock off the project area does not result in a net increase in the number of animals emitting methane.

Animals off the project area may not engage in the project activity (improved grazing management) while off the project area, resulting in potential unaccounted losses of SOC in the off-project locations they graze. In the absence of monitoring of off-project movements, proponents must conservatively assume that animals adopt baseline practices such as continuous or seasonal grazing that would result in losses of SOC.

Leakage from carbon losses may be set to zero if projects can demonstrate: the project area is fully fenced, boundaries are actively enforced, and animal herds are not grazed--intentionally or unintentionally--in areas outside of the project area. Otherwise, leakage emissions must be accounted for through the application of a conservative deduction.

The conservative deduction is calculated as a portion of project carbon removals in year *t* (calculated in Section 8.5) based on the proportion of the total number of animals in the project scenario and total grazing days spent outside the project area, as follows:

[14] This distance allows for possible uncertainty of herders as to the position of herds in or out of the project area and is a typical allowable buffer between ethnic group commun
al grazing lands [48]

$$LE_{D,y} = \frac{\sum_d \sum_c PN_{c,d}}{365 \times \sum_c PN_{c,y}} \times CR_y \tag{28}$$

Where:

$LE_{D,y}$	=	Leakage from temporary off-project grazing in year *y* (t CO_2e)
$Prop_{D,y}$	=	Proportion of the total number of animals and total grazing days spent outside the project area in year y (fraction)
$PN_{c,d}$	=	Project number of animals of each category *c* that grazed outside of the project on day *d* (head)
$PN_{c,y}$	=	Project number of animals of each category c in year y (head)
CR_t	=	Estimated carbon dioxide removals in year y (t CO_2e)
d	=	days grazed outside of the project area in year *y* (days)

Finally, total leakage emissions are the sum of the grazing displacement leakage calculated with *VMD0054* and the temporary off-project grazing leakage calculated above in Equation (28).

$$LK_y = \frac{MAX(0, LK_t - LK_{prior})}{years} + LE_{D,y} \tag{29}$$

Where:

LK_y	=	Total leakage emissions in year *y* (t CO_2e)
LK_t	=	Cumulative leakage up to year t (t CO2e) calculated with VMD0054
LK_{prior}	=	Cumulative leakage from VMD0054 between y = 0 and the prior verification event (t CO_2e)
years	=	Number of years during the verification period
$LE_{D,y}$	=	Leakage from temporary off-project grazing in year *y* (t CO_2e)

8.6 Net GHG Emission Reductions and Removals

Project activities can result in GHG emission reductions, CO_2 removals, or both.

GHG emission reductions before allocation of leakage emissions are quantified as:

$$ER_y = BEM_y - PEM_y + BEBB_y - PEBB_y + \Delta CO2_{ER,y} \tag{30}$$

Where:

ER_y	=	Emission reductions in year y (t CO_2e)
BEM_y	=	Average annual baseline emissions, from enteric methane, in year y, during the baseline period (t CO_2e)
PEMy	=	Project methane emissions from livestock in year *y* (t CO_2e)
$BEBB_y$	=	Average annual baseline emissions from biomass burning, in year y, during the baseline period (tCO_2e)
$PEBB_y$		Project biomass burning emissions, in year y (t CO_2e)
$\Delta CO2_{ER,y}$	=	Total carbon stock emissions reductions in year y (t CO_2e)

Note that emission reductions from avoided or reduced biomass burning shall not be accounted for where the same biomass is accounted for towards removals as a woody biomass carbon stock increase.

Additionally, note that PERy may be negative (indicating positive net project emissions) if BEM – PEMy < 0, and this will be counted in net GHG emissions reductions and removals (Ry) in Equation (31).

Net GHG emission reductions are quantified as:

$$ER_{NET,y} = ER_y \times UNC_y - LK_{ER,y} \tag{31}$$

Where:

$ER_{NET,y}$	=	Net GHG emission reductions in year y (t CO_2e)
ER_y	=	Emission reductions in year y (t CO_2e)
UNC_y	=	Uncertainty discount rate on emission reductions and removals by year *y* (%)
$LK_{ER,y}$	=	Leakage allocated to GHG emission reductions in year *y* (t CO_2e)

Leakage allocated to emission reductions ($LK_{ER,t}$) is calculated as:

$$LK_{ER,y} = LK_y \times \frac{ER_y}{ER_y + CR_y} \tag{32}$$

Where:

$LK_{ER,y}$	=	Leakage allocated to GHG emission reductions in year *y* (t CO_2e)
LK_y	=	Total leakage emissions in year y (t CO_2e)
ER_y	=	Emission reductions in year y (t CO_2e)
CR_y	=	Estimated carbon dioxide removals in year *t* (t CO_2e)

$\Delta CO2_{ER,annual,y}$ represents the annual net carbon stock change attributable to emissions reductions in year y. Because VM0032 employs cumulative accounting for carbon pools, the annualize net carbon stock change is quantified by: 1) calculating the cumulative net stock change since t = 0; 2) calculating the portion of cumulative net stock change that occurred in the current verification period; 3) annualizing the total stock change in the given verification period by dividing by the number of years in the verification period.[15]

[15] Although model simulations may generate carbon stock change estimates on an annual or sub-annual basis, cumulative accounting requires that annual vintages be derived as an average over the verification period. When model predictions of cumulative SOC stock change are updated, this can lead to adjustments in estimated SOC stock changes for prior years. However, credits already issued for past years cannot be revised. To ensure consistency, all SOC stock changes occurring within the current verification period are aggregated and then annualized over that period, so that each year's vintage reflects a proportional allocation of total credited removals.

$$\Delta CO2_{ER,y} = \frac{\Delta CO2_{ER,vp}}{years} \quad (33)$$

$$\Delta CO2_{ER,vp} = \Delta CO2_{ER,cml,y} - \Delta CO2_{ER,cml,prior} \quad (34)$$

Where:

$\Delta CO2_{ER,vp}$	=	Carbon stock emissions reductions in the current verification period (t CO_2e)
$\Delta CO2_{ER,cml,y}$	=	Cumulative carbon stock emissions reductions between y = 0 and y (t CO_2e)
$\Delta CO2_{ER,cml,prior}$	=	Cumulative carbon stock emissions reductions between y = 0 and the prior verification event (t CO_2e)
years	=	Number of years in the verification period

The value of $\Delta CO2_{ER,cml,t}$ depends on the magnitude and direction of cumulative carbon stock changes in the project and baseline scenario.

If cumulative carbon stock changes in the project scenario are greater than zero, only the portion of the net difference between project and baseline scenarios resulting from declines in the baseline scenario are attributable as emissions reductions. Thus, where $\Delta CO2_{PR,cml,y} > 0$:

$$\Delta CO2_{ER,cml,y} = \text{MIN}\left(0, \Delta CO2_{PR,cml,y}\right) - \text{MIN}\left(0, \Delta CO2_{BL,cml,t}\right) \quad (35)$$

Where:

$\Delta CO2_{ER,cml,y}$	=	Cumulative carbon stock emissions reductions between y = 0 and y (t CO_2e)
$\Delta CO2_{PR,cml,y}$	=	Cumulative carbon stock change in the project scenario from year y = 0 to y (t CO_2e)
$\Delta CO2_{BL,cml,y}$	=	Cumulative carbon stock change in the baseline scenario from year y = 0 to y (t CO_2e)

If cumulative carbon stock changes in the project scenario are less than or equal to zero, then the entirety of the difference between the project and baseline stock changes is attributable to emissions reductions, assuming the baseline stocks decrease more significantly than the project stocks. In the case that the baseline stocks lost less carbon or even gained carbon relative to the project scenario, the net stock change is calculated as an emission. Both scenarios are captured in the equation below, if $\Delta CO2_{wp,cml,y} \leq 0$:

$$\Delta CO2_{ER,cml,y} = \text{MIN}\left(0, \Delta CO2_{PR,cml,y}\right) - \text{MIN}(0, \Delta CO2_{BL,cml,y}) + \text{MAX}\left(0, \Delta CO2_{PR,cml,y}\right) - \text{MAX}(0, \Delta CO2_{BL,cml,y}) \quad (36)$$

Where:

$\Delta CO2_{ER,cml,y}$ = Cumulative carbon stock emissions reductions between y = 0 and y (t CO_2e)

$\Delta CO2_{PR,cml,y}$	=	Cumulative carbon stock change in the project scenario from year y = 0 to y (t CO_2e)
$\Delta CO2_{BL,cml,y}$	=	Cumulative carbon stock change in the baseline scenario from year y = 0 to y (t CO_2e)

A negative value for $\Delta CO2_{ER,cml,y}$ indicates the project scenario has emitted more CO_2 relative to the baseline scenario since t = 0.

Carbon dioxide removals occur when the cumulative carbon stock change in the project scenario is positive (i.e., the project carbon stock is higher than at the project start date). Then, possible annual stock variation includes:

1) Carbon stocks increase from year y= 0 to *y* in the baseline scenario and, to a greater extent, in the project scenario.[16]
2) Carbon stocks decrease from year y = 0 to y in the baseline scenario and carbon stocks increase from year y = 0 to y in the project scenario.[17]

Where cumulative carbon stock changes in the project scenario are less than or equal to 0, no carbon removals have occurred and CR_y = 0.

Otherwise, where cumulative carbon stock changes in the project scenario are greater than 0, the portion of net carbon stock change attributable to carbon dioxide removals in year t is:

$$CR_y = \frac{CR_{vp}}{years} \tag{37}$$

$$CR_{vp} = CR_{cml,y} - CR_{cml,prior} \tag{38}$$

Where:

CR_y	=	Estimated carbon dioxide removals in year y (t CO_2e)
CR_{vp}	=	Estimated carbon dioxide removals in the current verification period that is attributable to carbon dioxide removals (t CO_2e)
$CR_{cml,y}$	=	Estimated cumulative carbon dioxide removals between y = 0 and t (t CO_2e)
$CR_{cml,prior}$	=	Estimated cumulative carbon dioxide removals between y = 0 and the prior verification event (t CO_2e)
years	=	Number of years in the verification period

$$CR_{cml,y} = (\mathrm{MAX}(0, \Delta CO2_{PR,cml,y}) - \mathrm{MAX}(0, \Delta CO2_{BL,cml,y})) \tag{39}$$

[16] In this case, CO_2 removals would occur in the baseline scenario and the project activity enhances removals in the considered timeframe.

[17] In this case, the project activity leads to avoiding emissions that would occur in the baseline scenario in the considered timeframe, and increases carbon stocks beyond the level at the project start date, resulting in CO_2 removals.

If CR_t is negative (i.e., $CR_{cml,prior} > CR_{cml,t}$ or $\Delta CO2_{BL,cml,t} > \Delta CO2_{PR,cml,t}$) then negative removals must be considered as emissions and subtracted from Emission Reductions ER_t.

Net carbon dioxide removals are quantified as:

$$CR_{NET,y} = CR_y \times UNC_y - LK_{CR,y} \tag{40}$$

Where:

$CR_{NET,y}$	=	Estimated net carbon dioxide removals in year y (t CO_2e)
CR_y	=	Estimated carbon dioxide removals in year y (t CO_2e)
UNC_y	=	Uncertainty discount rate on emission reductions and removals by year *y* (%)
$LK_{CR,y}$	=	Leakage allocated to carbon dioxide removals in year *y* (t CO_2e)

Leakage allocated to carbon dioxide removals ($LK_{CR,y}$) is calculated as:

$$LK_{CR,y} = LK_y \times \frac{CR_y}{ER_y + CR_y} \tag{41}$$

Where:

$LK_{CR,y}$	=	Leakage allocated to carbon dioxide removals in year *y* (t CO_2e)
LK_y	=	Total leakage emissions in year y (t CO_2e)
CR_y	=	Estimated carbon dioxide removals in year y (t CO_2e)
ER_y	=	Emission reductions in year y (t CO_2e)

Net reductions and removals are quantified as:

$$ERR_{NET,y} = ER_{NET,y} + CR_{NET,y} \tag{42}$$

Where:

$ERR_{NET,y}$	=	Net reductions and removals in year y (t CO_2e)
$ER_{NET,y}$	=	Net reductions in year y (t CO_2e)
$CR_{NET,y}$	=	Net removals in year y (t CO_2e)

8.6.1 Carbon Stock Changes

Cumulative carbon stock change in the baseline scenario from t = 0 through year *t* is quantified as:

$$\Delta CO2_{BL,cml,y} = \Delta AWB_{BL,y} + \Delta SOC_{BL,y} \tag{43}$$

Where:

$\Delta CO2_{BL,cml,y}$	=	Cumulative carbon stock change in the baseline scenario from year y = 0 to y (t CO_2e)

$\Delta AWB_{BL,y}$	=	Cumulative carbon stock change in aboveground woody biomass in the baseline control sites through year *y* (t CO_2e)
$\Delta SOC_{BL,y}$	=	Cumulative baseline SOC carbon stock change through year *y* (t CO_2e)

Cumulative carbon stock change in the project scenario from year t = 0 to *t* is quantified as:

$$\Delta CO2_{PR,cml,y} = \Delta AWB_{PR,y} + \Delta SOC_{PR,y} \tag{44}$$

Where:

$\Delta CO2_{PR,cml,y}$	=	Cumulative carbon stock change in the project scenario from year y = 0 to y (t CO_2e)
$\Delta AWB_{PR,y}$	=	Cumulative project carbon stock change in aboveground woody biomass through year *y* (t CO_2e)
$\Delta SOC_{PR,y}$	=	Cumulative project SOC carbon stock change through year *y* (t CO_2e)

8.6.2 Ex ante Calculations of Net Emissions and Removals

The project must perform an ex-ante (before project) calculation of expected or estimated net emissions and removals. The key to making such a calculation is to define project quantitative management objectives for fire frequency and/or grazing management compared to baseline activities. The project proponent must do the following:

1) Show a table of baseline and proposed project scenario management activities.
2) Show a table of expected parameters and emissions and removals, and their uncertainties, associated with those management objectives; use data from the peer-reviewed literature, measure activities in the project area, or calculate with a model the resulting changes in emissions and removals associated with the management.
3) Calculate expected project scenario emissions and removals, and their uncertainties, based on these management targets.
4) Show a table of baseline emissions, project emissions and removals, leakage (if any), and total net greenhouse gas emissions and removals for each year of the project crediting period.

8.6.3 Estimation of Uncertainty

The *u*ncertainty is calculated on the basis of the half-width of the 90 percent Confidence Interval (CI), which is equal to 1.645 x standard error of the estimate, expressed as a percentage of the estimate of each emission or removal. The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [43] recommends using a Tier 2 approach to determine uncertainty where emission reductions are determined by a combination of measurements, published emission factors, and process models, such as a soil carbon model. Uncertainty must be calculated separately for emission reductions and removals, Uncertainty in removals may also include uncertainty in the increase in woody biomass carbon stocks total uncertainty may be calculated by calculating a pooled uncertainty according to the magnitude of removals. In this case, uncertainty in removals UR_y is driven by uncertainty in carbon stock changes.

$$UR_y = \frac{\left(\left(U\Delta WB_{PR,y} \times \Delta WB_{PR,y}\right)^2 + \left(U\Delta SOC_{PR,y} \times \Delta SOC_{PR,y}\right)^2\right)^{1/2}}{\Delta SOC_{PR,y} + \Delta WB_{PR,y}} \tag{43}$$

Where:

UR_y = uncertainty in removals, not including leakage, in year *y* (%)

$U\Delta WB_{PR,y}$ = uncertainty in project change in woody biomass carbon stocks in year *y* (%)

$U\Delta SOC_{PR,y}$ = uncertainty in project change in soil carbon stocks in year *y* (%)

$\Delta WB_{PR,y}$ = project change in woody biomass carbon stocks in year y (t CO_2e)

$\Delta SOC_{PR,y}$ = project change in soil carbon stocks in year y (tCO_2e)

Since net emissions for the project is based on a sum (subtraction of baseline from project) of project and baseline emissions, pooled uncertainty in emissions in year *y* is given by:

$$UE_y = \frac{\left(\left(BEM_y \times UBEM\right)^2 + \left(PEM_y \times UPEM_y\right)^2 + \left(BEBB_y \times UBEBB\right)^2 + \left(PEBB_y \times UPEBB_y\right)^2\right)^{1/2}}{BEM_y + PEM_y + BEBB_y + PEBB_y}$$

Where

UE_y = uncertainty in emissions in year y (%)

BEM_y = Average annual baseline emissions, from enteric methane, in year y, during the baseline period (t CO_2e)

PEM_y = Project methane emissions from livestock in year *y* (t CO_2e)

$UBEM$ = uncertainty in baseline enteric emissions (%)

$UPEM_y$ = uncertainty in project enteric emissions for the monitoring period ending in year *y* (%)

$BEBB_y$ = Average annual baseline emissions from biomass burning, in year y, during the baseline period (tCO_2e)

$PEBB_y$ = Project biomass burning emissions, in year y (t CO_2e)

$UBEBB$ = uncertainty in baseline emissions of methane and nitrous oxide from biomass burning (%)

$UPEBB_y$	= uncertainty in project emissions of methane and nitrous oxide from biomass burning for monitoring year ending in year y (%)

Each of the two component uncertainties are derived in detail below.

For calculating uncertainty in removals to soil carbon stocks when using a Modeled Approach, a Tier 2 approach involves conducting Monte Carlo simulations[3, 38], which must calculate R_y from equation (35) (see section 8.4.1) more than 100 times, with each calculation drawing randomly from hypothetical normal distributions of expected values of each parameter in the calculation, as defined by the mean and standard errors of each parameter. This simulation gives a mean and standard deviation of removals NR_y that are used to calculate uncertainty (equation (35)). Such Monte Carlo simulations may be done in online computing environments, such as the R Project for Statistical Computing [48], or even with macros developed for spreadsheets [44].

$$U\Delta SOC_{PR,y} = 1.645 \times 100 \times \frac{SD\left(MC\Delta SOC_{PR,y}, n\right)_c}{MC\Delta SOC_{PR,y} \times n^{1/2}}$$

(42)

Where:

$U\Delta SOC_{PR,y}$	= total uncertainty in net emission reductions and removals, not including leakage (%)
n	= number of Monte Carlo simulation runs performed (must be > 100)
$M\Delta SOC_{PR,y}$	= mean net emissions reductions and removals at year y, from n Monte Carlo calculations of $\Delta SOC_{PR,y}$ (tCO_2e)
$SD(M\Delta SOC_{PR,y},n)$	= standard deviation of $\Delta SOC_{PR,y}$ from n Monte Carlo simulations

8.6.3.1 Uncertainty in Emissions

For the calculation of uncertainty in emissions, BE, uncertainty arises in the calculation of enteric methane emissions and emissions of methane and nitrous oxide from biomass burning

In the case of proposed activities to alter fire frequency across different strata m (e.g. early versus late burned, soil carbon strata) is the pooled uncertainty across strata:

8.6.3.1.1 Uncertainty in baseline methane emissions from grazing animals (UBEM)

This uncertainty is calculated as

$$UBEM = \frac{\left(\sum_{c=1}^{k}(BEM_c \times UBEM_c)^2\right)^{\frac{1}{2}}}{\sum_{c=1}^{k} BEM_c}$$

(46)

Where:

$UBEM$	= Uncertainty in baseline methane emissions from grazing animals (%)
$UBEM_c$	= Uncertainty in baseline methane emissions from animals in category *c* (%)
BEM_c	= Baseline emissions from animals in category *c* (tCO_2e)

$UBEM_c$ is the uncertainty in methane emissions from animals in category c, as dictated by

whether the animals are ruminants, equids, or pigs (see Section 8.1.3.1). $UBEM_c$ is calculated from the uncertainty, for each animal category, in the regression equations predicting per animal daily methane emission (DME_c) based on the mean body weight ($UDME_c$) and the uncertainty in the arithmetic mean of animal counts (UBNc) during the baseline period.

To obtain UBN_c, first find $SEBN_c$, the standard error [50] of the arithmetic mean BN_c of the series' $N_{c,i}$ of animals in category *c* in count *i* of *n* counts or censuses.

$$SEBN_c = \frac{SD(N_{c,i})}{n^{1/2}}$$

(47)

Where:

$SEBN_c$	= Standard error of the arithmetic mean of animal counts in category *c*
$SD(BN_{c,i})$	= Standard deviation of the inverses of the count *i* of animals in category *c*
$N_{c,i}$	= Animals in category *c* in census *i* (head)
BN_c	= Arithmetic mean number of animals in category *c* (head) during the baseline period (head)
n	= Number of censuses

The 95 percent confidence interval-based uncertainty in the estimated number of animals in category *c* is:

$$UBN_c = 1.645 \times 100 \times \frac{SEBN_c}{BN_c}$$

(48)

Where:

UBN_c	= Uncertainty in the arithmetic mean of animal counts (%)
$SEBN_c$	= Standard error of the arithmetic mean of animal counts

BN_c	= Baseline number of animals of category *c* (head)
1.645	= Multiplier converts expression into half of a 90% confidence interval
100	= Multiplier converts expression into percent

$$UBEM_c = (UBN_c^2 + UDME_c^2)^{1/2} \qquad (49)$$

Where:

$UBEM_c$	= Uncertainty in baseline methane emissions from animals in category *c* (%)
UBN_c	= Uncertainty in the baseline arithmetic mean of animals of category *c* (%)
$UDME_c$	= Uncertainty in the regression for predicting daily methane emissions for animals of category *c* (%)

8.6.3.1.2 Uncertainty in baseline methane emissions from burning of biomass

In the case of project activities that increase burned area, uncertainty in BEBB (UBEBB) is driven by uncertainty in mean burned area over the *Y* (i.e., 10) years prior to the project start ($UMBA_m$) in stratum *m* (or mean area burned, ha), and uncertainty in mean within-stratum aboveground plant biomass , both woody and herbaceous fuel classes, t the end of the growing season, $UAPB_m$. [19].

$$UMBA_m = 1.645 \times 100 \times \frac{SD(MBA_m)}{MBA_m \times 10^{1/2}} \qquad (50)$$

Where:

$UMBA_m$	= uncertainty (%) in burned area within stratum *m*
$SD(MBA_m)$	= standard deviation in mean area burned in stratum *m* over the 10 years prior to project start (ha)
MBA_m	= Mean area burned in stratum *m* over the 10 years prior to project start (ha)
100	= converts the expression into percent
1.645	= converts the expression into half of a 90% confidence interval

Baseline Uncertainty in Aboveground Plant Biomass Prior to Fire

UAPBm arises from the 95 percent confidence interval among permanent sampling stations in clipped, dried, and weighed biomass.

$$UAPB_m = 1.645 \times 100 \times \frac{SD\left(APB_{m,zm}\right)}{\frac{\sum_{j=1}^{zm} APB_{m,j,0}}{z_m} \times {z_m}^{1/2}}$$

(51)

Where:

UAPB$_m$ = uncertainty in aboveground woody biomass within stratum *m*

SD(APB$_{m,zm}$) = standard deviation in aboveground plant biomass among z_m permanent sampling stations in stratum *m*

z_m = number of sampling stations in stratum *m*

APB$_{m,j,0}$ = aboveground plant biomass prior to fire at station *j* in stratum *m* (kg/ha) at the project start.

1.645 = converts the expression into half of a 90% confidence interval

Therefore, these two sources of uncertainty combine as

$$UBEBB = \frac{\left(\sum_{m=1}^{f} \frac{PA_m}{PA} (UAPB_m \times APB_m)^2 + \sum_{m=1}^{f} \frac{PA_m}{PA} \left(UMBA_m \times MBA_{m,y}\right)^2 +\right)^{1/2}}{\sum_{m=1}^{f} \frac{PA_m}{PA} APB_m + \sum_{m=1}^{f} \frac{PA_m}{PA} MBA_{m,y}}$$

(52)

Where:

UBEBB = Uncertainty in baseline methane emissions from burning of biomass

UMBA$_m$ = Uncertainty in the fire frequency in stratum *m*

UAPB$_m$ = Uncertainty in mean within-stratum aboveground plant biomass at the end of the growing season in stratum *m*

MBA$_{m,y}$ = Mean burned area in stratum *m* over the *y* years of the monitoring period.

APB$_{m,y,}$ = Mean aboveground plant biomass in stratum *m,* in year *y*

PA$_m$ = Area of stratum *m* (ha)

PA = Project area (ha)

f = number of burning strata

8.6.3.2 Uncertainty in the Baseline

For the calculation of baseline emissions and reductions, BER, uncertainty arises in the calculation of methane emissions only, because all other net emissions are conservatively assumed to be zero, unless increasing fire frequency is a proposed management activity. In this case:

$$UBE = UBM \tag{45}$$

Where:

UBE	=	Uncertainty in baseline emissions (%)
UBEM	=	Uncertainty in baseline methane emissions from grazing animals (%) (go to section 8.4.2.1.1)

In the case of proposed activities to alter fire frequency:

$$UBE = \frac{\left((BEM \times UBEM)^2 + \sum_{m=1}^{s} \frac{PA_m}{PA} (UBEBB_m \times BEBB_m)^2\right)^{1/2}}{BEM + \sum_{m=1}^{s} \frac{PA_m}{PA} BEBB_m} \tag{46}$$

Where:

UBE	=	Uncertainty in baseline emissions (%)
BEM	=	baseline methane emissions from animals across the project area (tCO_2e)
UBEM	=	Uncertainty in baseline methane emissions from grazing animals (%) (go to section 8.4.2.1.1)
PA_m	=	Area of stratum *m* (ha)
PA	=	Project area (ha)
$UBEBB_m$	=	Uncertainty in baseline methane emissions from burning of biomass (%) in stratum *m*
$BEBB_m$	=	baseline emissions from burning of biomass in stratum *m* (tCO_2e)

8.6.3.2.1 Uncertainty in baseline methane emissions from grazing animals (UBEM)

This uncertainty is calculated as

$$UBEM = \frac{\left(\sum_{c=1}^{k} (BEM_c \times UBEM_c)^2\right)^{\frac{1}{2}}}{\sum_{c=1}^{k} BEM_c} \tag{47}$$

Where:

UBEM	=	Uncertainty in baseline methane emissions from grazing animals (%)
BEM_c	=	Baseline emissions from animals in category *c* (tCO_2e)
$UBEM_c$		Uncertainty in baseline methane emissions from animals in category *c* (%)

UBEMc is the uncertainty in methane emissions from animals in category c, as dictated by whether the animals are ruminants, equids, or pigs (see Section 8.1.3.1). UBEMc is calculated from the uncertainty, for each animal category, in the regression equations predicting per animal daily methane emission (DMEc) based on the mean body weight (UDMEc) and the uncertainty in the arithmetic mean of animal counts (UBNc) during the baseline period.

To obtain UBN_c, first find $SEBN_c$, the standard error (Norris 1940) of the arithmetic mean BN_c of the series' $N_{c,i}$ of animals in category *c* in count *i* of *n* counts or censuses.

$$SEBN_c = \frac{SD(BN_{c,i})}{n^{1/2}} \tag{48}$$

Where:

$SEBN_c$	=	Standard error of the arithmetic mean of animal counts in category *c*
SD(BNc,i)	=	Standard deviation of the inverses of the count i of animals in category c
$BN_{c,i}$	=	Arithmetic mean number of animals in category c (head) during the baseline period (head)
n	=	Number of censuses

The 95 percent confidence interval-based uncertainty in the estimated number of animals in category *c* is:

$$UBN_c = 1.6449 \times 100 \times \frac{SEBN_c}{BN_c} \tag{49}$$

Where:

UBN_c	=	Uncertainty in the arithmetic mean of animal counts (%)
1.6449	=	Multiplier converts expression into half of a 90% confidence interval
$SEBN_c$	=	Standard error of the arithmetic mean of animal counts
BN_c	=	Baseline number of animals of category *c* (head)

$$UBEM_c = \left(UBN_c{}^2 + UDME_c{}^2\right)^{\frac{1}{2}} \tag{50}$$

Where:

$UBEM_c$	=	Uncertainty in baseline methane emissions from animals in category *c* (%)
UBN_c	=	Uncertainty in the baseline arithmetic mean of animals of category *c* (%)
$UDME_c$	=	Uncertainty in the regression for predicting daily methane emissions for animals of category *c* (%)

8.6.3.2.2 Uncertainty in baseline methane emissions from burning of biomass

In the case of project activities that increase burned area, uncertainty in BEBB (UBEBB) is driven by uncertainty in mean burned area over the *Y* (i.e., 10) years prior to the project start ($UMBA_m$) in stratum *m* (or mean area burned, ha), and uncertainty in mean within-stratum aboveground plant biomass , both woody and herbaceous fuel classes, t the end of the growing season, $UAPB_m$. (Dempewolf et al. 2007).

$$UMBA_{m,BY} = 1.6449 \times 100 \times \frac{SD\left(MBA_{m,BY}\right)}{MBA_{m,BY} \times BY^{1/2}} \tag{51}$$

Where:

$UMBA_{m,BY}$	=	uncertainty (%) in burned area within stratum *m*
1.6449	=	converts the expression into half of a 90% confidence interval
$SD(MBA_{m,BY})$	=	standard deviation in fire frequency in stratum *m* over *BY* years in the baseline period
BY	=	number of years in baseline period for which burned area is measured
$MBA_{m,BY}$	=	mean proportion of area burned during the baseline period *BY years*

Baseline Uncertainty in Aboveground Biomass Prior to Fire

$UAPB_m$ arises from the 95 percent confidence interval among permanent sampling stations in clipped, dried, and weighed biomass.

$$UAPB_m = 1.6449 \times 100 \times \frac{SD\left(APB_{m,zm}\right)}{\frac{\sum_{j=1}^{zm} APB_{j,m,0}}{z_m} \times {z_m}^{1/2}} \tag{52}$$

Where:

$UAPB_m$	=	uncertainty in aboveground plant biomass within stratum *m*
1.6449	=	converts the expression into half of a 90% confidence interval
$SD(APB_{m,zm})$	=	standard deviation in aboveground plant biomass among z_m permanent sampling stations in stratum *m*
$APB_{j,m,0}$	=	aboveground plant biomass prior to fire at station *j* in stratum *m* (kg/ha) at the project start.
z_m	=	number of sampling stations in stratum *m*

Therefore, these two sources of uncertainty combine as

$$UBEBB = \frac{\left(\sum_{m=1}^{f} \frac{PA_m}{PA}\left(UAPB_m \times APB_m\right)^2 + \sum_{m=1}^{f} \frac{PA_m}{PA}\left(UMBA_m \times MBA_{m,y}\right)^2 + \right)^{1/2}}{\sum_{m=1}^{f} \frac{PA_m}{PA} APB_m + \sum_{m=1}^{f} \frac{PA_m}{PA} MBA_{m,y}} \tag{53}$$

Where:

UBEBB	=	Uncertainty in baseline methane emissions from burning of biomass
PA_m	=	Area of stratum *m* (ha)
PA	=	Project area (ha)
$UAPB_m$	=	Uncertainty in mean within-stratum aboveground plant biomass at the end of the growing season in stratum *m*

APB_m	=	Mean aboveground plant biomass in stratum *m*
$UMBA_m$	=	Uncertainty in the fire frequency in stratum *m*
$MBA_{m,y}$	=	Mean burned area in stratum *m* over the *y* years of the monitoring period
f	=	number of burning strata

8.6.3.3 Uncertainty under the Project Scenario

Uncertainty under the project scenario using a weighted uncertainty approach is determined by uncertainty in project emissions and/or in carbon stocks, weighted by the magnitude of each and the proportion of project area in each stratum, for each year of the monitoring period.

$$UNR_y = \left(UPE_y{}^2 + UNCSS_y{}^2\right)^{\frac{1}{2}} \quad (54)$$

Where:

UNR_y	=	
UPE_y	=	Uncertainty in project emissions (%)
$UNCSS_y$	=	Uncertainty in project carbon stocks changes (%)

$$UPE_y = \frac{\left((PEM \times UPEM)^2 + \sum_{m=1}^{s} \frac{PA_m}{PA}\left(PEBB_{m,y} \times UPEBB_{m,y}\right)^2\right)^{1/2}}{PEM + \sum_{m=1}^{s} \frac{PA_m}{PA} PEBB_{m,y}} \quad (55)$$

Where:

UPE_y	=	Uncertainty in project emissions (%)
PEM	=	project methane emissions by animals during the monitoring period (tCO2e)
UPEM	=	Uncertainty in project methane emissions from grazing animals (%)
PA_m	=	Area of stratum *m* (ha)
PA	=	Project area (ha)
$PEBB_{m,y}$	=	project emissions from biomass burning in stratum *m* in year *y* (tCO2e)
$UPEBB_{m,y}$	=	Uncertainty in project methane emissions from burning of biomass (%)

For uncertainty in project carbon stocks changes $UNCCS_y$

$$UNCCS_y = \frac{\left(\sum_{m=1}^{s} \frac{PA_m}{PA}\left(\Delta SOC_{PR,y} \times UPRS_{m,y}\right)^2 + \sum_{m=1}^{s} \frac{PA_m}{PA}\left(PRAWPBC_{m,y} \times UPRAWPBC_m\right)^2\right)^{1/2}}{\sum_{m=1}^{s} \frac{PA_m}{PA} \Delta SOC_{PR,y} + \sum_{m=1}^{s} \frac{PA_m}{PA} PRAWPBC_{m,y}}$$

Where:

$UNCCS_y$	=	Uncertainty in project carbon stocks changes (%)
PA_m	=	area (ha) in stratum *m*
PA	=	project area (ha)
$\Delta SOC_{PR,y}$	=	Project SOC stock change through year *y* (tCO_2e)
$UPRS_{m,y}$	=	Uncertainty in project reductions from SOC stock changes in stratum *m* though year *y* (%)
$PRAWPBC_{m,y}$	=	
$UPRAWPBC_m$	=	Uncertainty in project changes in woody plant biomass carbon (%)
$WB_{PR,y}$	=	Project aboveground woody biomass carbon through year y (t CO2e)

8.6.3.3.1 Uncertainty in Project Methane Emissions

This uncertainty is calculated as

$$UPEM = \frac{\left(\sum_{c=1}^{k}(PEM_c \times UPEM_c)^2\right)^{\frac{1}{2}}}{\sum_{c=1}^{k} PEM_c} \quad (56)$$

Where:

$UPEM$	=	Uncertainty in project methane emissions from grazing animals during the monitoring period (%)
PEM_c	=	project methane emissions from animals in category *c* (tCO_2e)
$UPEM_c$	=	Uncertainty in project methane emissions from animals in category *c* (%)

$UPEM_c$, is the uncertainty in methane emissions calculated from the uncertainty, for each animal category, in the regression equations for per animal daily methane production and the uncertainty in the arithmetic mean of animal censuses for category *c*, PN_c, during the monitoring period.

$$UPEM_c = \left(UPN_c{}^2 + UDME_c{}^2\right)^{\frac{1}{2}} \quad (57)$$

Where:

$UPEM_c$	=	
UPN_c	=	
$UDME_c$	=	

$$UPN_c = 1.6449 \times 100 \times \frac{SD\left(PN_{c,Y}\right)}{PN_{c,Y} \times Y^{1/2}} \quad (58)$$

Where:

UPN_c	=	
1.6449	=	Multiplier that converts the expression into half of a 90% confidence interval

$SD(PN_{c,Y})$	=	Standard deviation of animal counts in category *c* across *Y* years of the monitoring period
$PN_{c,Y}$		
Y		Years in the monitoring period

$MPN_{c,Y}$	= Arithmetic mean of animal numbers in category *c* (head) across *Y* years of the monitoring period.
$UPME_c$	= Uncertainty in the regression, taken from the literature (Table 7) for predicting daily methane emissions for animals of category *c*

8.6.3.3.2 Uncertainty in Project Emissions from Burning of Biomass

In the case of project activities that increase fire frequency, uncertainty in *PEBB*, or *UPEBB*, is driven by uncertainty in area burned ($UPBA_m$) in stratum *m*, and uncertainty in mean within-stratum aboveground plant biomass at the end of the growing season, $UAPB_m$. $UPBA_m$ arises from the 95 percent confidence interval in annual variation in proportion of area burned over the period since last validation]. $UAPB_m$ arises from the 95 percent confidence interval among permanent sampling stations in clipped, dried, and weighed biomass. Consequently:

$$UPEBB_{m,y} = \left(UPBA_{m,Y}{}^{2} + UAPB_{m,y}{}^{2}\right)^{\frac{1}{2}} \tag{59}$$

Where:

$UPEBB_{m,y}$	=	Uncertainty in project methane emissions from burning of biomass (%)
$UPBA_{m,Y}$	=	Uncertainty in the project burned area in stratum *m* over the *Y* years of the monitoring period (%)
$UAPB_{m,y}$	=	

$$UPBA_{m,Y} = 1.6449 \times 100 \times \frac{SD(PBA_{m,Y})}{PBA_{m,y} \times Y^{1/2}} \tag{60}$$

$UPBA_{m,Y}$	=	
1.6449	=	
$SD(PBA_{m,Y})$	=	Standard deviation in area of stratum *m* burned during the *Y* years of the monitoring period
$PBA_{m,y}$	=	Mean burned area (ha) in stratum *m* burned during the *Y* years of the monitoring period
Y	=	

$$UAPB_m = 1.6449 \times 100 \times \frac{SD\left(APB_{m,y,zm}\right)}{\frac{\sum_{j=1}^{zm} APB_{m,j,y}}{z_m} \times {z_m}^{1/2}} \quad (61)$$

Where:

$UAPB_m$	=	Uncertainty in mean within-stratum aboveground plant biomass at the end of the growing season in stratum *m* (%)
$SD(APB_{m,y,zm})$	=	standard deviation in aboveground plant biomass across the z_m stations in stratum *m* in year *y*.
$APB_{m,j,y}$	=	mean aboveground plant biomass prior to burning season at station *j* in stratum *m* (kg/ha)
z_m	=	number of sample plots in stratum *m*
1.6449	=	multiplier that converts the expression into half of a 90% confidence interval

8.6.3.3.3 Uncertainty in Project Soil Organic Carbon Stock Change

Measured Approach

Under a measured approach, uncertainty in SOC stock change, $UPRS_{m,y}$ in stratum *m* over the *Y* years of the monitoring period is obtained from the 95 percent confidence interval, of measured change in SOC across z_m sampling stations in stratum *m*.

$$UPRS_{m,Y} = 1.645 \times 100 \times \frac{SD(\Delta SOC_m)}{\Delta SOC_m \times z_m} \quad (62)$$

Where:

$UPRS_{m,Y}$	=	uncertainty in project SOC stock change in stratum *m* during the *Y* years of the monitoring period (%)
1.645	=	
SD(ΔSOC_m)	=	
ΔSOC_m	=	Mean of the difference in SOC between the beginning of the project or monitoring period, year *v*, and the last year of monitoring *Y*, across z_m sampling stations in stratum *m* (tCO_2e /ha)
z_m	=	

$$\Delta SOC_m = \frac{44}{12}\frac{1}{z_m}\sum_{j=1}^{z_m}\left(SOC_{m,j,Y} - SOC_{m,j,y}\right) \quad (57)$$

$SD\Delta SOC_m$	= Standard deviation of ΔSOC in stratum *m* during the monitoring period across z_m sampling stations in stratum *m*
Y	= Number of years in the monitoring period
z_m	= Number of sampling stations in stratum *m*
1.6449	= Multiplier that converts the numerator into half of a 90% confidence interval
100	= Multiplier that converts the expression into percent

Modeled Approach

Under a modeled approach, $UPRS_{m,Y}$ during the *Y* years of the monitoring is obtained from the calculated 90 percent confidence interval, from a Monte Carlo simulation of modeled changes in soil carbon (see Sections 8.4.2 and 8.1.3.3) averaged across *n* model runs in stratum *m*.

$$UPRS_{m,Y} = 1.6449 \times 100 \times \frac{SDMOD\Delta SOC}{MOD\Delta SOC \times n^{1/2}}$$

(58)

Where:

$UPRS_{m,Y}$	= Uncertainty in project removals through increased soil carbon in stratum *m* during the *Y* years of the monitoring period (%)
$SDMOD\Delta SOC_m$	= Standard deviation from Monte Carlo simulation of more than 100 modeled SOC estimates of change in project SOC for stratum *m* between modeled baseline year 0 and year *L*, the length of the project lifetime for stratum *m*
$MOD\Delta SOC_{m,L}$	= Mean modeled change in project SOC carbon stocks for stratum *m* between modeled baseline year 0 and year *L*, the length of the project lifetime or the number of years to reach equilibrium, whichever is less (tCO_2e /ha)
n	= Number of times simulation is run (must be $\geq$ 100)
1.6449	= Multiplier to convert standard error into a 95% confidence interval
100	= Multiplier to convert to percent

8.6.3.3.4 Uncertainty in Project Emissions and Removals from Woody Plant Biomass.

Measured Approach

Uncertainty in emissions from loss or gain of aboveground woody plants $UPERWP_{m,y}$ arises from three sources of among plot variation (see below). Consequently, uncertainty in removals or emissions from changes in aboveground woody biomass, $UPERWP_{m,y}$, must be calculated as follows:

$$UPRWBC_{m,y} = \frac{\left(\left(PWB_{m,y} \times UPWB_{m,y}\right)^2 + \left(PWB_{m,Y} \times UPWB_{m,Y}\right)^2 + (WCD_m \times UWCD_m)^2\right)^{1/2}}{PWB_{m,y} + PWB_{m,Y} + WCD_m}$$

(59)

(1) Among-plot variation in aboveground woody biomass in stratum m at the beginning of the monitoring period, $UPWB_{m,y}$,

$$UPWB_{m,y} = 1.6449 \times 100 \times \frac{SD\left(PWB_{m,zm,y}\right)}{PWB_{m,y} \times z_m^{1/2}}$$

(60)

Where:

$SD(PWB_{m,zm})$	= Standard deviation of project woody biomass across *z* sampling stations in stratum *m* in year *y*, at the beginning of the monitoring period.
$PAWB_{m,y}$	= Mean project woody plant biomass across *z* sampling stations in stratum *m* in year *y*, the beginning of the monitoring period,(kg/ha)
1.6449	= Multiplier to convert expression to 95% confidence interval
100	= Multiplier to convert expression to percent

(2) Among plot variation in initial (baseline) aboveground woody biomass in year *Y* (end) of the monitoring period in stratum *m*: $UWB_{m,Y}$,

$$UPWB_{m,Y} = 1.6449 \times 100 \times \frac{SD\left(PWB_{m,zm,Y}\right)}{PWB_{m,Y} \times z_m^{1/2}}$$

(61)

Where:

$SD(PWB_{m,zm,Y})$	= Standard deviation of projectwoody biomass across z_m sampling stations in year *Y*, the end of the monitoring period
$PWB_{m,Y}$	= Mean project woody biomass across *z* sampling stations in stratum *m* in year *Y*, the end of the monitoring period (kg/ha)

1.6449 = Multiplier to convert expression to 90% confidence interval

100 = Multiplier to convert expression to percent

and

(3) Among plot variation in wood carbon density: $UWCD_m$

$$UWCD_m = 1.6449 \times 100 \times \frac{SD(WCD_{m,zm})}{WCD_m \times z_m^{1/2}}$$

(62)

Where:

$SD(WCDm,$zm)	= standard deviation of wood carbon density across z_m sampling stations in stratum *m*
$WCD_{m,}$	= mean wood carbon density across z_m sampling stations in stratum *m* (gC/g wood)
1.6449	= multiplier to convert expression to 95% confidence interval
100	= multiplier to convert expression to percent

8.6.4 Conservative Approach

Calculations of emissions reductions and removals are conservative because:

1) Baseline methane emissions use the mean over the years of baseline livestock counts for baseline emissions and an arithmetic mean for the project scenario leading to a conservative estimate for reductions in methane emissions (Section 8.1.3.1).

2) Initial baseline carbon stock level for modelled (activity-based) emission reductions must be the maximum of the previous 10 years, as required by the latest version of the VCS requirements [47, 49] unless the baseline carbon stock(s) is/are increasing. In the case of a modeled approach, the baseline equilibrium carbon stock is set to this maximum and then compared to the modeled future equilibrium SOC at the end of the project lifetime, whichever is less (Section 8.1.3.3).

3) Because models used in the modeled approach must be validated for the project with data from the project area, no model correction is necessary. However, model predictions must meet the statistical requirements for validation assessment (see section 8.1.3.3 and Appendix II) to assure that the model does not overestimate removals. All parameter choices should make model predictions conservative.

4) Emissions reductions are subject to reductions for uncertainty, as required by the latest version of the VCSrules [47, 49] in the modeled approach, with uncertainty determined from 90 percent confidence intervals from standard errors calculated during Monte Carlo simulations (Section 8.4.2).

8.6.5 Uncertainty Deduction

If total project uncertainty in year *y*, based on 90 percent confidence intervals, $UNR_y \leq 10$ percent, then no deduction must result for uncertainty.

If $UNR_y > 10$ percent, then the modified discounted value, $R_y = R_y^{disc}$ for net anthropogenic GHG removal by sinks to account for uncertainty must be, as prescribed in section 2.4 of the Methodology Requirements Version 4.4:

$$UNC_y = \left(1 - \frac{UNR_y}{t_{\alpha=90\%}} \times t_{\alpha=66\%}\right) \tag{67}$$

$t_{\alpha=10\%} \times t_{\alpha=66.6\%}$

Where:

UNC_y	= Uncertainty discount rate on emission reductions and removals by year *y* (%)
UNR_y	= Total project uncertainty %
$t_{\alpha=90\%}$,	= *t*-statistic for the two-sided 90% confidence interval, approximately 1.645
$t_{\alpha=66\%}$,	= *t*-statistic for the two-sided 66% confidence interval, approximately 0.4307

For *Y* years of the monitoring period,

$$R_Y = \sum_{y=1}^{d} R_y{}^{disc} + \sum_{y=1}^{u} R_y \tag{68}$$

Where:

d	= Number of years in which net removal must be discounted
u	= Number of years in which removals are not discounted

Y	= Number of years in the monitoring period *(d + u)*
R_y^{disc}	= Discounted net GHG emission reductions and removals by year *y* (tCO2e)
R_y	= Net GHG emission reductions and removals in year *y* (tCO2e)

8.7 Calculation of Verified Credit Units

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

$$VCU_y = VCU_{ER,y} + VCU_{CR,y} \tag{63}$$

Where:

VCU_y	=	Number of VCUs in year y (t CO_2e)
$VCU_{ER,y}$	=	Number of Verified Carbon Units resulting from project activities leading to reductions in year y
$VC_{CR,y}$	=	Number of Verified Carbon Units resulting from project activities leading to removals in year y

The number of VCUs resulting from project activities leading to reductions that may be issued in year y is calculated as:

$$VCU_{ER,y} = ER_{NET,y} - Bu_{ER,y} \tag{64}$$

Where:

$VCU_{ER,y}$		
$ER_{NET,y}$	=	Estimated net reductions in year y (t CO_2e)
$Bu_{ER,y}$	=	Buffer credits to be deducted from reductions in year y (t CO_2e)

The number of buffer credits that must be deposited is calculated by multiplying the non-permanence risk rating by the net change in carbon stocks (see most recent version of the *VCS Standard*[18]). The buffer credits deducted from reductions are quantified as:

$$Bu_{ER,y} = \Delta CO2_{ER,y} \times NPR\%$$

Where:

$NPR\%$	=	Overall project non-permanence risk rating converted to a percentage (%)

[18] For example, this is included in Section 3.2.10 of the *VCS Standard, v4.7*.

The number of VCUs resulting from project activities leading to removals that may be issued in year y is calculated as:

$$VCU_{CR,y} = CR_{NET,y} - Bu_{CR,y} \tag{65}$$

Where:

$CR_{NET,y}$	=	Estimated net removals in year y (t CO_2e)
$Bu_{CR,y}$	=	Buffer credits to be deducted from removals in year y (t CO_2e)

The buffer credits deducted from removals are quantified as:

$$Bu_{CR,y} = CR_{NET,y} \times NPR\%$$

9 MONITORING

Given applicability conditions and allowable conservative exclusions, monitoring focuses on measuring the key parameters for calculating emissions and removals, demonstrating project management activities, and measuring changes in SOC. The project activities key to changing methane emissions are altering the number and species composition of livestock grazing animals and/or species composition of forage plants, altering duration, timing, and intensity of grazing, and/or changing fire frequency, intensity, and any accompanying vegetation change (such as in woody biomass). Changes in SOC density under the project scenario must also be monitored and may be stratified according to management practices or soil and climatic conditions. Monitoring of soil, vegetation, grazing intensity and occurrence and intensity of fires must fully employ the permanent sampling stations discussed in Section 8.1.2.

9.1 Data and Parameters Available at Validation

Data/Parameter	BN_c
Data unit	head
Description	Baseline number of animals of category c
Equations	(4)
Source of data	Measured in project area
Value applied	As determined by the project area

Justification of choice of data or description of measurement methods and procedures applied	Arithmetic mean number of animals of each category over the baseline period. Animal counts may be obtained by direct ground censuses, ranch records, censuses of households for livestock numbers owned per household multiplied by number of households, aerial surveys, government inventories, or other methods.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$N_{c,i}$
Data unit	head
Description	Animals in category c during count i during the baseline period
Equations	
Source of data	Measured in the project area
Value applied	As determined by the project area
Justification of choice of data or description of measurement methods and procedures applied	Historical animal counts can be obtained in many different ways, including, but not exclusive to, direct ground censuses, ranch records, censuses of households for livestock numbers owned per household multiplied by number of households, aerial surveys, or government inventories.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	W_C
Data unit	kg
Description	Average body weight during the baseline period for animals of category c
Equations	
Source of data	Measured in project area or obtained from published sources relevant to the project area
Value applied	As determined by the project area

Justification of choice of data or description of measurement methods and procedures applied	Project proponents should obtain accurate mean body weight for the animal class. In open pastoralist systems, livestock owners are not likely to know the weights of their animals and values may need to be taken from outside sources, such as peer-reviewed literature, reports from development projects or government sources for the breed of animal or area relevant to the project area (for example, country, continental region).
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$DMEF(W_c)$
Data unit	L CH_4 / day
Description	Daily emission factor as a function of animal weight for category c
Equations	
Source of data	Allometric equations provided in Franz et al. (2010)
Value applied	As determined by the project areaN/A
Justification of choice of data or description of measurement methods and procedures applied	Estimates are obtained from an allometric formula presented in the literature based on body masses of different species of grazing or browsing animals on the project area. For details see section 8.1.3.1
Purpose of data	Calculation of baseline emissions
Comments	None

Table 9: Table for Calculating Baseline Methane Emissions from Animal Censuses.

Grazing Animal Category					Animal Counts (Head)						Methane Emissions	
Species	Sex/Age	Weight (kg)	Annual Methane Emissions/ Animal	Per Animal Uncertainty[1]	Year 1	Year 2	Year 3	Year 4	Harmonic Mean	Uncertainty in Animal Counts	Methane Emissions for Category (tCO2e)	Uncertainty in Methane Emissions
Species 1												
Species 2												
Species 3												
Species 4												
										Total Emissions		

[1] Based on uncertainty in regression models that calculate methane emissions from body mass (see Table 3)

Species-specific weights on the left-hand side are used to calculate annual methane emissions per animal using equation 3 (section 8.1.3.1). Methane emissions per animal are then multiplied by the mean number of animals (equation 3) to estimate annual methane emissions for the animal category. Uncertainty per animal (from Table 8 in section 8.1.3.1) and uncertainty in the mean (equation 41 in section 8.4.2) combine in equation 43 to calculate overall uncertainty in methane emissions. This table must be included in the project description.

9.1.1 PARAMETERS FOR BASELINE CALCULATION OF EMISSIONS FROM BURNING OF BIOMASS

For projects that intend to manage fire, the project description must show the equation (Equation 4) used to calculate BEBB and display a table showing estimated mean area burned for each stratum *m* and season (early versus late if fire seasons are accounted for), initial unburned aboveground plant biomass ($APB_{m,b}$), with 95 percent CI and uncertainties (95 percent CI/estimate, expressed as a percentage) for each and calculated BEBB with for each project stratum. Note that strata for estimating emissions or aboveground woody plant biomass carbon stocks biomass burning may be different from strata used to estimate changes in soil carbon stocks affected and may also be different than those used for estimating biomass

Data/Parameter	$APB_{m,b}$
Data unit	kg d.m./ha
Description	Mean total aboveground plant biomass in stratum m for fuel class *b* (summer or wet season)
Equations	
Source of data	Measured

Value applied	
Justification of choice of data or description of measurement methods and procedures applied	Measured at permanent sampling stations within each stratum m by clipping, drying (at 25-50 oC) and weighing aboveground vegetation from one or more small quadrats. If different fuel classes are accounted, mean biomass of each fuel class (e.g., herbaceous, fine woody, coarse woody) must be reported. Measured at the beginning of the dry season in the tropics or beginning of the cold or burning season in temperate climates. Must be measured in the project area 1-2 years before the project start date, or within the first year of the monitoring period and prior to the first prescribed burn. In the case of prescribed fire to control woody shrubs, biomass must be measured prior to the prescribed burn.
Purpose of data	Caclulation of baseline emissions
Comments	None

Data/Parameter	GWP_{CH4}
Data unit	t CO_2e/t CH_4
Description	Global warming potential for methane
Equations	
Source of data	IPCC Sixth Assessment Report, 2021
Value applied	28
Justification of choice of data or description of measurement methods and procedures applied	Support arguments provided in the data source
Purpose of data	Calculation of baseline and project emissions
Comments	None

Data/Parameter	GWP_{N2O}
Data unit	t CO_2e / t N_2O
Description	Global warming potential for nitrous oxide
Equations	
Source of data	IPCC Sixth Assessment Report, 2021

Value applied	265
Justification of choice of data or description of measurement methods and procedures applied	Support arguments provided in the data source
Purpose of data	Calculation of baseline and project emissions
Comments	None

Data/Parameter	$WB_{m,j,0}$
Data unit	kg/ha
Description	Woody biomass in stratum m at station j in the beginning of the monitoring period (at the project start, y = 0, or the year of last verification)
Equations	
Source of data	Measured in permanent sampling plots
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	Woody biomass has two copmponents – aboveground and belowground. Aboveground biomass is measured in circular quadrats centered at each permanent sampling station j. Diameter at breast height (dbh, 1.5 m) of each woody stem > 5 cm dbh, appropriate for grassland, savanna and grassy woodland applications, must be measured. Procedures must follow those detailed in MacDicken (1997). Woody stem mass must be then estimated from dbh using allometric equations published in peer-reviewed journals appropriate to the dominant woody species in the project area. For example, projects in savannas dominated by Pinus spp., Quercus spp. Vachellia spp., or Brachystegia spp would use different allometric equations to convert dbh into stem biomass. Belowground biomass of each stem is estimated similarly from dbh but using different allometric equations, as reported in peer-reviewed published literature for belowground biomass. Estimated above- and belowground biomasses are added to obtain total biomass / stem, and then total biomass per stem for each stem is then summed over all stems > 5 dbh in the plot.
Purpose of data	Calculation of project emissions
Comments	None

Data/Parameter	BC_G
Data unit	kg biomass/kg biomass burned
Description	Baseline combustion factor for savanna/grassland
Equations	
Source of data	Hoffa et al. (1999) or most recent version of the *IPCC Guidelines for National Greenhouse Gas Inventories*
Value applied	0.5 or default from Table 2.6 respectively
Justification of choice of data or description of measurement methods and procedures applied	It is unlikely that all aboveground biomass is combusted in fire, but this fraction is difficult to measure accurately during past years because biomass remaining after fire must be measured immediately following fire (Hoffa et al. 1999). The fraction of biomass combusted usually averages around 0.75 (Hoffa et al. 1999) and setting BCG = 0.5 makes the potential impact of increasing fire under the project scenario conservative in its likelihood to reduce emissions.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	EF_{BG}
Data unit	g CH_4/kg biomass burned
Description	Emission factor for the burning of grassland
Equations	
Source of data	Akagi et al. (2011)
Value applied	1.9
Justification of choice of data or description of measurement methods and procedures applied	
Purpose of data	Caclulation of baseline and project emissions
Comments	None

Data/Parameter	$BMAF_{b,m}$

Data unit	kg / ha
Description	Biomass of fuel class b after fire in stratum m
Equations	
Source of data	Measured
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	Fuel class based on classes defined in determination of the emission factors for CH4 or N2O, such as for example herbaceous, fine woody, and coarse woody, as in the Australian fire abatement emissions protocol - Savanna fire management - emissions avoidance method - DCCEEW and whether for example the stratum later experienced fire early in the dry season (first 50% of dry season days) or late. Thus, a given project for example might have six fuel classes – early herbaceous, early fine woody, early coarse woody, late herbaceous, late fine woody, late coarse. Biomass is measured by clipping herbaceous and fine woody plant material in replicate quadrats within the circular plots around permanent stations where standard forest inventory methods are used to estimate aboveground coarse woody biomass for stems with > 5 cm dbh. These ground measurements can be used to calibrate remote sensing methods, such as high-resolution satellite imagery, LIDAR, or drone images, later used to estimate biomass over a greater proportion of the project area than the circular plots.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$BM_{b,m}$
Data unit	kg/ha
Description	Biomass of fuel class b before fire in stratum m
Equations	
Source of data	Measured
Value applied	As determined for the project area
Justification of choice of data or description of measurement methods and procedures applied	Fuel classes are determined by emission factors for CH_4 or N_2O and must include at least herbaceous, fine woody, and coarse woody. Biomass may vary depending on timing of fire (e.g., in first 50% of dry season days, in last 50% of dry season days), so it may be appropriate to split fuel classes determined by emission factor into additional classes based on timing of fire (e.g., early herbaceous, late herbaceous).

	Herbaceous and fine woody plant material must be measured by clipping vegetation in replicate quadrats within circular plots around permanent stations. Standard forest inventory methods must be used to estimate aboveground coarse woody biomass for stems with >5 cm dbh, using habitat-appropriate allometric models to estimate tree carbon content. Allometric equations must be: 1) specific to the ecosystem type within the same ecoregion (defined at the biome level) or Holdridge life-zone as the region in which the project is located; or 2) specific to the species, genus, or family within the same ecoregion or Holdridge life-zone as the region in which the project is located. Ground measurements of herbaceous, fine woody, and coarse woody plant material can be used to calibrate remote sensing methods, such as high-resolution satellite imagery, LiDAR, or drone images, that may then be used to estimate biomass over the rest of the project area. Ground-based LiDAR (e.g., using tripod or vehicle) can be an accurate alternative to on-the-ground inventories. Airborne LiDAR must be limited to drones, airplanes, or any other technology that provides sufficient resolution to detect low-height vegetation and small changes in tree shape as a result of fires. Satellite-based LiDAR may only be used where the project proponent demonstrates that fine biomass changes in low-height vegetation are detectable. Use of LiDAR must be associated with a calibration protocol that shows matches between on-the-ground woody biomass measurements and LiDAR measurements.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$CF_{b,m}$
Data unit	%
Description	Baseline combustion factor for fuel class b in stratum m (mean proportion of biomass burned)
Equations	
Source of data	calculated
Value applied	As determined in/for the project area

Justification of choice of data or description of measurement methods and procedures applied	Combustion factors are calculated from the proportion of biomass lost between before and after fire, where biomass is measured at multiple permanent sampling stations which then experience fire. Fuel class based on classes defined in determination of the emission factors for CH4 or N2O, such as for example herbaceous, fine woody, and coarse woody, as in the Australian fire abatement emissions protocol in reference [71] and whether for example the stratum later experienced fire early in the dry season. Project proponents should provide justification for the date thresholds used for early or late fires. Thus, a given project for example might have six fuel classes – early herbaceous, early fine woody, early coarse woody, late herbaceous, late fine woody, late coarse.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$EF_{CH4,b,m}$
Data unit	g CH_4 / kg biomass burned
Description	Emission factor for methane for fuel class b in stratum m
Equations	
Source of data	Measurement or Peer-reviewed literature
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	1. Measure emission factors using gas exchange measurement equipment and experimental combustion 2. If measurement of emission factors is not possible or feasible, then use literature values, with values obtained from the literature corresponding to each fuel class and season of burning. For example, if fuel classes herbaceous, fine woody and coarse woody are to be used, then emission factors for each fuel class must be used and justified from peer-reviewed literature or IPCC defaults. 3. If emission factors for separate fuel classes are not available, then fuel classes can be combined (e.g. both woody combined) Published data should provide information to calculate uncertainty (SE, sample size) for each emission factor
Purpose of data	Calculation of emissions from biomass burning
Comments	

Data/Parameter	$EF_{N2O,b,m}$
Data unit	g N_2O / kg biomass burned
Description	Emission factor for nitrous oxide for fuel class b in stratum m
Equations	
Source of data	Measurements, or Estimates from peer-reviewed literature if measurements are not possible.
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	1. Measure emission factors using gas exchange measurement equipment and experimental combustion 2. If measurement of emission factors is not possible or feasible, then use literature values, with values obtained from the literature corresponding to each fuel class and season of burning. For example, if fuel classes herbaceous, fine woody and coarse woody are to be used, then emission factors for each fuel class must be used and justified from peer-reviewed literature or IPCC defaults. 3. If emission factors for separate fuel classes are not available, then fuel classes can be combined (e.g. both woody combined) Published data should provide information to calculate uncertainty (SE, sample size) for each emission factor.
Purpose of data	Calculation of emissions from biomass burning
Comments	None

The emission factors for methane and nitrous oxide may be obtained from the literature, either from global values (IPCC Guidelines for National Greenhouse Gas Inventories) or Tier 2 habitat specific values (Laris et al. 2021).

Data/Parameter	MBA_m
Data unit	ha
Description	Mean area burned in stratum m over the 10 years prior to project start
Equations	

Source of data	Remote-sensing data
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	This may be obtained by using satellite products, such as MODIS Burned Area Product[19] (as detailed in Section 9.3.5) that provide polygons of burned areas for 15-day periods throughout the dry or burning season. A GIS program like Quantum GIS (2.6)[20], and other programs like IDRISI[21] or ArcGIS, may perform similar functions. Project proponents may also use dated aerial photographs or accurate hand-drawn maps accompanied by records of where and when land parcels burned.
Purpose of data	Calculation of baseline emissions
Comments	None

9.1.2 Parameters for Calculation of Baseline SOC

Data/Parameter	$DEPTH_{m,j,0}$
Data unit	cm
Description	Soil core depth in stratum m at station j at time y = 0 (i.e., at the start of the project or since the last verification)
Equations	
Source of data	Measured in project area
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	At each sampling station j, according to standard methods (Knops and Tilman 2000; Nelson and Sommers 1996), soil must be taken from at least 3 soil cores (with 10 cores at each site recommended to reduce uncertainty) to a depth that accounts for the vast majority (> 80 percent) of SOC in the soil column, reflects depth to hardpans or bedrock, or matches calculations from soil carbon models. Multiple cores may be well-mixed into a single composite sample for analysis.
Purpose of data	Calculation of baseline emissions
Comments	None

[19] http://modis.gsfc.nasa.gov/)

[20] Quantum GIS 2.4 can be downloaded for free at https://www.qgis.org

[21] http://www.clarklabs.org

Data/Parameter	SOC%m,j,0
Data unit	dimensionless
Description	Proportion SOC at station j in stratum m at year y = 0 (i.e., at the start of the project or since the last verification)
Equations	
Source of data	Measured in project area
Value applied	
Justification of choice of data or description of measurement methods and procedures applied	The baseline for the measured offset approach is based on increasing SOC. Tracked at the level of j = 1 to zm individual sampling stations in each stratum because offset will be based on demonstrating changes in SOC at individual stations and then summing increments. At each sampling station j, according to standard methods (Knops and Tilman 2000; Nelson and Sommers 1996), soil must be taken from at least 3 soil cores (with 10 cores at each site recommended to reduce uncertainty) to a depth that accounts for the vast majority (> 80 percent) of SOC in the soil column, reflects depth to hardpans or bedrock, or matches calculations from soil carbon models. Multiple cores may be well-mixed into a single composite sample for analysis. Multiple stations must be sampled within each stratum so as to determine a 95 percent confidence interval. Organic carbon concentrations must be measured in appropriate academic or industrial laboratories that use either chemical (Walkley and Black 1934) combustion or appropriately calibrated spectral analysis methods. IR methods must be calibrated by regression, with R2 > 0.90, of IR measurement with measurement by chemical or combustion methods. Graphs of regression of IR versus combustion or chemical methods must be shown. There must be no significant bias (ie, slope 95 percent confidence interval must include 1) intercept 95 percent CI must include 0. Bias must be determined by evaluating percent bias (positive or negative) following equation (5) (see detailed description of bias evaluation in Section Error! Reference source not found.) and cannot exceed + 10%. If an IR spectrometer is to be used, the project proponent must show all calibration data in a table with spectral emissions and measurements of soils or plants and graphs showing the regressions of spectral data against measurements.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$BULK_{m,j,0}$
Data unit	Mg dry soil / m³ or, equivalently, g / cm³ (Note Mg/m³ are equivalent to g/cm³, the unit most commonly reported by laboratory analyses.)
Description	Bulk density in stratum m at station j in year y = 0
Equations	
Source of data	Measured in project area
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	At each sampling station j, according to standard methods (Knops and Tilman 2000; Nelson and Sommers 1996), soil must be taken from at least 3 soil cores (with 10 cores at each site recommended to reduce uncertainty) to a depth that accounts for the vast majority (> 80 percent) of SOC in the soil column, reflects depth to hardpans or bedrock, or matches calculations from soil carbon models. Multiple cores may be well-mixed into a single composite sample for analysis. Known volumes of soil from the cores must be sieved to remove rocks, pebbles, and coarse fragments, and then the remainder dried (5 days at 45ºC or equivalent) and weighed to determine bulk density (Hao et al. 2007).
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$BCMSOC_{m,j,B}$
Data unit	t C / ha
Description	Modeled SOC density at station j in stratum m for year B at the beginning of the 10-year baseline period that predicts the current, measured initial soil carbon stock ($SOC_{m,j,0}$)
Equations	
Source of data	SOC density predicted by project's chosen carbon stock dynamic model
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	Conservative estimate of maximum baseline soil carbon stock, as predicted by the project's chosen soil carbon dynamic model by backcasting from measured baseline soil carbon stock using parameter inputs reflective of baseline conditions (grazing, fire, animal density, soil type, climate, etc.

Purpose of data	Calculation of baseline carbon stocks
Comments	

Data/Parameter	$MSOC_{m,0}$
Data unit	t C / ha
Description	Modeled SOC in stratum m for year y = 0 (see section 8.1.3.3)
Equations	
Source of data	Soil carbon dynamic model
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	A model published in the peer-reviewed scientific literature that predicts changes in SOC density as a function of various input variables, which may include aboveground production, belowground production, precipitation, temperature, fire frequency, initial SOC, soil texture, and grazing intensity and possibly other factors detailed in the peer-reviewed article(s) describing the model. For more details, see section 8.1.3.3.2 and Appendix II
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	PA_m
Data unit	ha
Description	Area of stratum m
Equations	
Source of data	Measured in project area
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	Digitized polygons demarcating different strata, which may reflect variation across the project area in, for example, management jurisdictions (e.g., ranches, communities, protected areas), soil types, vegetation types, climate zones. For more details on stratification, see section 8.1.2.2 and Appendix I.

Purpose of data	Calculation of baseline emissions
Comments	

Data/Parameter	$SOC\%_{m,j,0}$
Data unit	Dimensionless proportion
Description	Percent SOC in dry soil from the entire soil profile to the chosen depth in stratum m at station j in year y = 0 (i.e., at the start of the project or since the last verification)
Equations	
Source of data	Measured in project area
Value applied	As determined in/for the project area
Justification of choice of data or description of measurement methods and procedures applied	The baseline for the measured offset approach is based on increasing SOC. Tracked at the level of j = 1 to z_m individual sampling stations in each stratum because offset will be based on demonstrating changes in SOC at individual stations and then summing increments. At each sampling station j, according to standard methods (Knops and Tilman 2000; Nelson and Sommers 1996), soil must be taken from at least 3 soil cores (with 10 cores at each site recommended to reduce uncertainty) to a depth that accounts for the vast majority (> 80 percent) of SOC in the soil column, reflects depth to hardpans or bedrock, or matches calculations from soil carbon models. Multiple cores may be well-mixed into a single composite sample for analysis. Multiple stations must be sampled within each stratum to determine a 95 percent confidence interval. Organic carbon concentrations must be measured in appropriate academic or industrial laboratories that use either chemical (Walkley and Black 1934) combustion or appropriately calibrated spectral analysis methods. IR methods must be calibrated by regression, with $R^2 \geq 0.90$, of IR measurement with measurement by chemical or combustion methods. Graphs of regression of IR versus combustion or chemical methods must be shown. There must be no significant bias (i.e., slope 95 percent confidence interval must include 1) intercept 95 percent CI must include 0. Bias must be determined by evaluating percent bias (positive or negative) following equation (5) (see detailed description of bias evaluation in Section **Error! Reference source not found.**) and cannot exceed $\pm$ 10%. If an IR spectrometer is to be used, the project proponent must show all calibration data in a table with spectral emissions and measurements of soils or plants and graphs showing the regressions of spectral data against measurements.

Purpose of data	Calculation of baseline emissions
Comments	

9.1.3 Parameters for Soil Carbon Models

Soil carbon models may require anywhere from a few to more than 80 parameters, so there is no definitive list of parameters that would apply to all models. However, in evaluating whether a modeled approach is feasible or desirable, the following parameters are likely to be key inputs into soil carbon models. Each parameter may vary among strata, depending on the size of the project area and underlying variation in soil type and plant species composition. Parameters must yield a predicted SOC density.

Data/Parameter	MAP_m
Data unit	mm/year
Description	Mean annual precipitation in stratum m
Equations	
Source of data	Precipitation maps from government or peer-reviewed published sources, nearby weather stations, or rain gauges
Value applied	
Justification of choice of data or description of measurement methods and procedures applied	A key variable that affects a number of processes driving SOC
Purpose of data	Calculation of baseline emissions
Comments	

Data/Parameter	$ST_{j,m,y}$
Data unit	oC
Description	Soil temperature at station j in stratum m in month y
Equations	
Source of data	Measured in project area
Value applied	

Justification of choice of data or description of measurement methods and procedures applied	Must be measured monthly or at least seasonally with a digital thermometer with probes inserted to at least ½ the depth at which SOC will be sampled (i.e., to 10 cm if soil will be sampled and modeled to 20 cm (Piñeiro et al. 2006)
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	SAND%j,m and/or CLAY%j,m and/or SILT%j,m
Data unit	%
Description	Proportion of soil that is sand, silt, and or clay at station j in stratum m
Equations	
Source of data	Measured in project area
Value applied	
Justification of choice of data or description of measurement methods and procedures applied	Soil collected to desired depth at each sampling station must be mixed, and subsample analyzed for clay, silt, and sand fractions in a professional laboratory. Some models require percent sand, some percent clay and some percent of all three particle classes, sand, silt, and clay.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	*GIj,m*
Data unit	dimensionless
Description	Mean annual grazing intensity at station j in stratum m
Equations	
Source of data	Measured
Value applied	
Justification of choice of data or description of measurement methods and procedures applied	Measured at each sampling station prior to validation by either: 1) Comparing clipped biomass at least at the end of the growing season, or more frequently for some models, inside and outside small

	(1 m2) fences. GIj,m = 1 – (biomass outside/biomass inside). Biomass is clipped, dried at 25 – 50 oC, and weighed. 2) Visually estimating historical grazing intensity from a calibrated observation method (R2>0.80 correlation between measured GI (from option 1 above and observational method)) based on species composition, bare ground, and vegetation height.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	*MAPLC j,m*
Data unit	dimensionless
Description	Mean aboveground plant cellulose plus lignin at sampling plot j in stratum m
Equations	
Source of data	Measured in project area
Value applied	
Justification of choice of data or description of measurement methods and procedures applied	SOC is often closely related to inputs of these forms of carbon because they resist microbial decomposition.
Purpose of data	Calculation of baseline emissions
Comments	None

In addition, soil carbon models may likely use burned area of season and fuel class *b* in stratum *m* , $PBA_{m,b}$ and the loss of biomass following fire, and initial $SOC_{m,j,0}$.

Tracking parameters at each sampling station allows the chosen soil carbon model(s) to be tested at many locations and under different conditions. This improves the ability to infer whether data fit model predictions and, as it turns out, reduces sample size needed to achieve a desired margin of error in estimating changes in carbon stocks (Appendix I).

These parameters must be input into the chosen soil carbon model(s) to calculate the SOC parameters described below, which are used in the quantification of removals.

Data/Parameter	*MSOCm,j,b*

Data unit	t C/ha
Description	Modeled SOC at station j in stratum m for each year b during the baseline period
Equations	
Source of data	SOC model
Value applied	
Justification of choice of data or description of measurement methods and procedures applied	SOC models applied must meet with the modeling requirements described in Section Error! Reference source not found.8.1.3.4.
Purpose of data	Calculation of baseline emissions
Comments	None

Data/Parameter	$PSOC^{eq}_{m,j,}$
Data unit	t C/ha
Description	Modeled SOC at equilibrium at station j in stratum m
Equations	
Source of data	SOC model
Value applied	
Justification of choice of data or description of measurement methods and procedures applied	SOC models applied must meet with the modeling requirements described in Section 8.3.48.1.3.3.
Purpose of data	Calculation of project emissions
Comments	None

9.1.4 Parameters for Removals from Woody Plant Biomass

Data/Parameter	C
Data unit	kg C / kg biomass

Description	Proportion of wood composed of carbon
Equations	
Source of data	CDM, A/R Methodological Tool: Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities, and MacDicken, 1997
Value applied	0.45
Justification of choice of data or description of measurement methods and procedures applied	Conversion factor for calculating AWBC from measured aboveground woody biomass (see Section 9.1.2 for description of measuring/monitoring aboveground woody biomass parameter).
Purpose of data	Calculation of project removals and emissions from biomass burning
Comments	

Data/Parameter	$PRSAWB_{m,p,0}$
Data unit	kg C / kg biomass
Description	Initial project area woody biomass in paired polygon p as interpreted from calibrated remote sensing model
Equations	
Source of data	Sentinel-2, LIDAR, Worldview-3
Value applied	Measured
Justification of choice of data or description of measurement methods and procedures applied	Reflectance data, interpreted from analytical algorithm such as a neural network, machine, learning, or artificial intellence to predict average aboveground woody biomass within a polygon within the project area at the start of the project. Polygon is paired with a similar polygon off the project area selected to match the conditions in the project polygon. For more details see Verra Methdology VM0047.
Purpose of data	Calculation of project removals and emissions from changes in AWB carbon stocks resulting from project activity
Comments	None

Data/Parameter	$CRSAWB_{m,p,0}$
Data unit	kg C / kg biomass

Description	Initial control plot woody biomass in paired polygon p to project area stratum m, as interpreted from calibrated remote sensing model
Equations	
Source of data	Sentinel-2, LIDAR, Worldview-3
Value applied	Measured
Justification of choice of data or description of measurement methods and procedures applied	Reflectance data, interpreted from analytical algorithm such as a neural network, machine, learning, or artificial intelligence to predict average aboveground woody biomass within a polygon within the project area at the start of the project. Polygon is paired with a similar polygon **on** the project area selected to match the conditions in the project polygon. For more details see Verra Methdology VM0047.
Purpose of data	Calculation of project removals and emissions from changes in AWB carbon stocks resulting from project activity
Comments	None

9.2 Data and Parameters Monitored

9.2.1 Project Enteric Methane Emissions

Parameters monitored are those needed to calculate reductions from reduced methane emissions from animals plus any increases in emissions of methane from burning of biomass and leakage. Unlike when determining the baseline, the arithmetic mean of the counts during the project crediting period must be used to ensure a conservative estimate of reductions in methane emissions relative to baseline emissions, which are calculated with the mean livestock counts over the baseline period (Ferger 1931).
For permissible methods of conducting an animal census, see Section 9.3.3.

Data/Parameter	$PN_{c,y}$
Data unit	number
Description	Number of animals of category c in the project area during year y
Equations	
Source of data	Measured in project area

Description of measurement methods and procedures to be applied	
Frequency of monitoring/recording	Annual
QA/QC procedures to be applied	Based on records of livestock numbers, interviews of grazing managers, coordinators, herders, or other administrative staff. Records should be kept as paper and electronic copies.
Purpose of data	Calculation of project emissions
Calculation method	N/A
Comments	The project description must provide a table, similar to that for calculating baseline methane emissions, of counts or estimates of numbers of grazing animals, PN_c, for each year during the monitoring period, sorted by the k categories in the project area: species, breed (if applicable), sex, and age, plus the respective live body weights (W_c) of each category, with 95% percent CI and uncertainties. The table must also contain the uncertainty in daily methane emissions and the uncertainty in the arithmetic mean count based on the equations in Section 8.6.3.3.1. Table 10 below may be used as a template.

Data/Parameter	$MPN_{c,Y}$
Data unit	number
Description	Arithmetic mean number of animal numbers in category c across Y years of the monitoring period
Equations	
Source of data	Measured in project area
Description of measurement methods and procedures to be applied	Measured as the arithmetic mean of one or more years' animal censuses during the verification period
Frequency of monitoring/recording	Annual

QA/QC procedures to be applied	Based on records of livestock numbers, interviews of grazing managers, coordinators, herders, or other administrative staff. Records should be kept as paper and electronic copies.
Purpose of data	Calculation of project emissions
Calculation method	N/A
Comments	The project description must provide a table, similar to that for calculating baseline methane emissions, of counts or estimates of numbers of grazing animals, PNc, for each year during the monitoring period, sorted by the k categories in the project area: species, breed (if applicable), sex, and age, plus the respective live body weights (Wc) of each category, with 95% percent CI and uncertainties. The table must also contain the uncertainty in daily methane emissions and the uncertainty in the arithmetic mean count based on the equations in Section 8.6.3.3.1. Table 12 below may be used as a template.

Data/Parameter	$W_{c,y}$
Data unit	kg
Description	Average body weight during year *y* for animals of category *c*
Equations	
Source of data	Measured in project area or obtained from published sources relevant to the project area
Description of measurement methods and procedures to be applied	Project proponents should obtain accurate mean body weight for the animal class. In open pastoralist systems, livestock owners are not likely to know the weights of their animals and values may need to be taken from outside sources, such as peer-reviewed literature, reports from development projects or government sources for the breed of animal or area relevant to the project area (for example, country, continental region).
Frequency of monitoring/recording	Every 5 years or as necessary to accommodate changes in the use of different animal breeds
QA/QC procedures to be applied	If weights are directly measured, Data to be stored off-site (Cloud or data storage service), on paper, and in storage media directly controlled by the project proponent, including hard drives, flash drives, etc.

	Field crews will be trained and use tablets or other digital data entering devices for entering information so that data is automatically uploaded to the off-site storage as soon as wireless connections are available. This avoids errors in transcribing data. Digital data will later be printed for archival against loss of access to digital storage media (drives or offsite online storage)
Purpose of data	Calculation of project emissions
Calculation method	N/A
Comments	None

Table 10: Table for Calculating Project Methane Emissions from Animal Censuses.

Grazing Animal Category					Animal Census (Number of Animals)						Methane Emissions	
Species	Sex/Age	Weight (kg)	Annual Methane Emissions/ Animal	Per Animal Uncertainty[1]	Year 1	Year 2	Year 3	Year 4	Arithmetic Mean	Uncertainty in Animal Counts	Methane Emissions for Category (tCO2e)	Uncertainty in Methane Emissions
Species 1												
Species 2												
Species 3												
Species 4												
										Total Emissions		

[1] Based on uncertainty in regression models that calculate methane emissions from body mass (see Table 3)

Species-specific weights on the left-hand side are used to calculate annual methane emissions per animal using equation 3 (section 8.1.3.1). Methane emissions per animal are then multiplied by the arithmetic mean number of animals to estimate annual methane emissions for the animal category. Uncertainty per animal (from Table 7 in section 8.1.3.1) and uncertainty in the baseline arithmetic mean (equation 41 in section 8.4.2) combine in equation 43 to calculate overall uncertainty in methane emissions. This table must be included in the project description.

9.2.2 Project Emissions from Burning of Biomass

For projects that intend to increase fire frequency, the project description must show the equation (Equation (4)) used to calculate $PEBB_{m,y}$ in year y for each project stratum m. All projects that alter fire frequency must display a table showing burned area in year y pre-fire aboveground plant biomass ($APB_{j,m,y}$), and post-fire aboveground plant biomass at stations where fire occurred ($APB_{j,m,y}$) with 95 percent CI and uncertainties for each and calculated.

Data/Parameter	$PBA_{m,y}$
Data unit	ha
Description	Area burned in stratum m during project year y. Note stratum in this case may refer to a season of burn as well as strata generated by other factors (soils, management, etc.)
Equations	
Source of data	Measured
Description of measurement methods and procedures to be applied	Measured by mapping burned areas with aerial photography or in projects with extensive area (> 10,000 ha), interpreting satellite images, such as MODIS with published algorithms for assessing burned area (Dempewolf et al. 2007)[19]. Photography or satellite image interpretations must be confirmed by records of known burned areas or ground assessments of burns in the past year.
Frequency of monitoring/recording	Every 15 days during the burning season
QA/QC procedures to be applied	Follow procedures in De Santis et al. (2010) and Dempewolf et al. (2007)
Purpose of data	Calculation of project emissions

Calculation method	
Comments	None

Data/Parameter	*APBj,m,y*
Data unit	kg dry mass/ha
Description	Aboveground plant biomass at station j in stratum m in year y at the beginning of the dry/cold or burning season
Equations	
Source of data	Measured
Description of measurement methods and procedures to be applied	Measured at permanent sampling stations within each stratum m by clipping, drying (at 25-50 oC) and weighing aboveground vegetation from one or more small quadrats. Measurements from all quadrats must be averaged for each sampling station j. Measured at the beginning of the dry/cold/burning season in temperate climates (McNaughton 1985; Ritchie et al. 1998).
Frequency of monitoring/recording	Annually
QA/QC procedures to be applied	Samples must be dried in a professional drying oven for 3 days at 45-60oC or be air-dried in sunshine for 4-7 days to a constant mass
Purpose of data	Calculation of project emissions
Calculation method	
Comments	None

Data/Parameter	$PBA_{m,y}$
Data unit	ha
Description	Area burned in stratum m during monitoring year y
Equations	

Source of data	Measured
Description of measurement methods and procedures to be applied	Measured by mapping burned areas with aerial photography or in projects with extensive area (> 10,000 ha), interpreting satellite images, such as MODIS with published algorithms for assessing burned area (Dempewolf et al. 2007). Photography or satellite image interpretations must be confirmed by records of known burned areas or ground assessments of burns in the past year.
Frequency of monitoring/recording	If timing of burning is considered to influence fuel class or is the basis for stratification, imagery should be analyzed twice annually – once halfway through the fire season to assess area burned "early" and once at the end of the fire season to assess area burned "late." Otherwise, analysis once per year is sufficient.
QA/QC procedures to be applied	If aerial photography or drone imagery are used, images should be stored off-site (Cloud or data storage service), on paper, and in storage media directly controlled by the project proponent, including hard drives, flash drives, etc.
Purpose of data	Calculation of project emissions from biomass burning and removals to woody and soil carbon from fire management
Calculation method	N/A
Comments	None

Data/Parameter	$PBMAF_{b,m,y}$
Data unit	kg / m^2
Description	Project biomass of fuel class *b* in stratum *m* after fire in monitoring year *y*
Equations	
Source of data	Measured
Description of measurement methods and procedures to be applied	Measured at each sampling station using either ground measurements or calibrated remote-sensing methods. Ground measurements involve standard forest inventory methods (USDA 2018) coupled with allometric conversions of tree size metrics (like diameter at breast height [dbh]) to total tree carbon mass, or by using calibrated new high resolution remote sensing methods such as LIDAR (Zhou et al. 2022).Ground measurements also include estimates of fine woody and

	herbaceous biomass from clipped, dried aboveground plant material in multiple quadrats associated with the larger forest inventory plot. Calibrated remote-sensing methods may also be used, either with high resolution spectral satellite imagery, such as, for example, from Sentinel, Quickbird, etc. or LIDAR imagery from drone imagery. Such imagery should be calibrated at the start of the project using ground measurements from each sampling station. Standard materials for forest inventory plots – dbh tape, 25+meter measuring tape
Frequency of monitoring/recording	Annually or in the last year of a monitoring period
QA/QC procedures to be applied	Data to be stored off-site (Cloud or data storage service), on paper, and in storage media directly controlled by the project proponent, including hard drives, flash drives, etc. Field crews will be trained and use tablets or other digital data entering devices for entering information so that data is automatically uploaded to the off-site storage as soon as wireless connections are available. This avoids errors in transcribing data. Digital data will later be printed for archival against loss of access to digital storage media (drives or offsite online storage)
Purpose of data	Calculation of project emissions
Calculation method	N/A
Comments	None

Data/Parameter	$PBM_{b,m,y}$
Data unit	kg / ha
Description	Project pre-fire biomass of fuel class b in stratum m for year y
Equations	
Source of data	Measured at each sampling station using either ground measurements or calibrated remote-sensing methods. Ground measurements involve standard forest inventory methods (USDA 2018) coupled with allometric conversions of tree size metrics (like diameter at breast height [dbh]) to total tree carbon mass, or by using calibrated new high resolution remote sensing methods such as LIDAR (Zhou et al. 2022).Ground measurements also include estimates of fine woody and herbaceous biomass from clipped, dried aboveground plant material in multiple quadrats associated with the larger forest inventory plot.

	Calibrated remote-sensing methods may also be used, either with high resolution spectral satellite imagery, such as, for example, from Sentinel, Quickbird, etc. or LIDAR imagery from drone imagery. Such imagery should be calibrated at the start of the project using ground measurements from each sampling station.
Description of measurement methods and procedures to be applied	Annually or in the last year of a monitoring period Standard materials for forest inventory plots – dbh tape, 25+meter measuring tape
Frequency of monitoring/recording	As determined in/for the project area
QA/QC procedures to be applied	Data to be stored off-site (Cloud or data storage service), on paper, and in storage media directly controlled by the project proponent, including hard drives, flash drives, etc. Field crews will be trained and use tablets or other digital data entering devices for entering information so that data is automatically uploaded to the off-site storage as soon as wireless connections are available. This avoids errors in transcribing data. Digital data will later be printed for archival against loss of access to digital storage media (drives or offsite online storage)
Purpose of data	Calculation of project emissions
Calculation method	Measured at each sampling station using either ground measurements or calibrated remote-sensing methods. Ground measurements involve standard forest inventory methods (USDA 2018) coupled with allometric conversions of tree size metrics (like diameter at breast height [dbh]) to total tree carbon mass, or by using calibrated new high resolution remote sensing methods such as LIDAR (Zhou et al. 2022).Ground measurements also include estimates of fine woody and herbaceous biomass from clipped, dried aboveground plant material in multiple quadrats associated with the larger forest inventory plot. Calibrated remote-sensing methods may also be used, either with high resolution spectral satellite imagery, such as, for example, from Sentinel, Quickbird, etc. or LIDAR imagery from drone imagery. Such imagery should be calibrated at the start of the project using ground measurements from each sampling station.
Comments	None

Data/Parameter	$PCF_{b,m,y}$
Data unit	%

Description	Project combustion factor for fuel class b in stratum m in year y (mean proportion of biomass burned). This can be changed by project activities, such as a shift from late season to early season burning, and thus is expected to be different under project activities and in different years.
Equations	
Source of data	Calculated from project measurements
Description of measurement methods and procedures to be applied	N/A
Frequency of monitoring/recording	Annually, or twice annually if fuel classes or project strata distinguish early versus late season burning
QA/QC procedures to be applied	Calculations in project spreadsheets should transparently reference measured biomass data used to calculate it
Purpose of data	Calculation of project emissions
Calculation method	Calculated using equation (16), section 8.2.2.1
Comments	None

Data/Parameter	PEBBN2O,y
Data unit	t CO2e
Description	Project emissions of N2O from biomass burning on the project area in year y
Equations	
Source of data	Calculated from project measurements
Description of measurement methods and procedures to be applied	N/A
Frequency of monitoring/recording	

QA/QC procedures to be applied	
Purpose of data	Calculation of project emissions
Calculation method	
Comments	None

9.2.3 Parameters for Calculating SOC carbon stock changes

If a measured approach is taken, then the critical measurement is of SOC density at the end of the monitoring period at each sampling station, according to standard methods (Knops and Tilman 2000; Nelson and Sommers 1996). Soil must be taken from three or more pooled soil cores (with 10 cores at each site recommended to reduce uncertainty) at each station to a desired depth (cm) For more details, see section 9.1.4.

In a modeled approach, these same procedures must apply when monitoring soil carbon for the purposes of reassessing the chosen soil carbon model. In this case there may be a calibration period of Z years (typically 5-7 years) that is long enough to detect changes in SOC and likely longer than the monitoring periods used in a modeled approach.

Data/Parameter	$DEPTH_{m,j,y}$
Data unit	cm
Description	Soil core depth in stratum m at station j in year y = 0 (i.e., at the start of the project or since the last verification)
Equations	
Source of data	Measured in project area
Description of measurement methods and procedures to be applied	Soil must be taken from at least three soil cores (with 10 cores at each site recommended to reduce uncertainty) at each station j to a depth that accounts for the vast majority (> 80 percent) of SOC in the soil column, reflects depth to hardpans or bedrock, or matches calculations from soil carbon models. Multiple cores may be well-mixed into a single composite sample for analysis. Soil auger
Frequency of monitoring/recording	At the end of the monitoring period for measured approach projects, or, for modeled approach, after a desired monitoring period for re-calibrating the chosen soil carbon model based on its ability to predict changes in soil carbon during the monitoring period.
QA/QC procedures to be applied	Depth cored must be the same as for baseline soil carbon sampling (see 9.1.3). However, the depth used in calculating SOC after Y years of

	project activities must be adjusted to account for changes in bulk density such that $DEPTH_{m,j,Y}$ x $BULK_{m,j,Y}$ = $DEPTH_{m,j,0}$ x $BULK_{m,j,0}$. This ensures that equal masses of soil are compared between year 0 and year Y
Purpose of data	Calculation of project emissions
Calculation method	
Comments	None

Data/Parameter	$SOC\%_{m,j,y}$
Data unit	Dimensionless proportion
Description	Percent SOC in stratum m at station j in year y
Equations	
Source of data	Measured in project area
Description of measurement methods and procedures to be applied	Soil must be taken from at least three soil cores (with 10 cores at each site recommended to reduce uncertainty) at each station j to a depth that accounts for the vast majority (> 80 percent) of SOC in the soil column, reflects depth to hardpans or bedrock, or matches calculations from soil carbon models. Multiple cores may be well-mixed into a single composite sample for analysis. The organic carbon concentrations must be measured in appropriate academic or industrial laboratories with chemical (Walkley and Black 1934) automated, calibrated analytical machines or with project-area calibrated infra-red IR spectrometers (Knadel et al. 2011).
Frequency of monitoring/recording	At the end of the monitoring period for measured approach projects, or, for modeled approach, after a desired monitoring period for re-validating the chosen soil carbon model based on its ability to predict changes in soil carbon during the monitoring period.
QA/QC procedures to be applied	The organic carbon concentrations must be measured in appropriate academic or industrial laboratories with chemical (Walkley and Black 1934) automated, calibrated analytical machines or with project-area calibrated infra-red IR spectrometers (Knadel et al. 2011). IR methods must be calibrated by regression, with $R^2 \geq 0.90$, of IR measurement with measurement by chemical or combustion methods. Graphs of regression of IR versus combustion or chemical methods must be shown. There must be no significant bias (i.e., slope 95 percent confidence interval must include 1) intercept 95 percent CI must include 0, which will ensure that MBIAS, following equation (5) (Moriasi et al. 2007) is between -10% and +10%. If an IR spectrometer is to be

	used, the project proponent must show all calibration data in a table with spectral emissions and measurements of soils or plants and graphs showing the regressions of spectral data against measurements.
Purpose of data	Calculation of project emissions
Calculation method	
Comments	None

Data/Parameter	$BULK_{m,j,Y}$
Data unit	Mg dry soil / m^3 or, equivalently, g / cm^3 (Note Mg/m^3 are equivalent to g/cm^3, the unit most commonly reported by laboratory analyses.)
Description	Bulk density in stratum m at station j in year Y
Equations	
Source of data	Measured in project area
Description of measurement methods and procedures to be applied	Soil must be taken from at least three soil cores (with 10 cores at each site recommended to reduce uncertainty) at each station j to a depth that accounts for the vast majority (> 80 percent) of SOC in the soil column, reflects depth to hardpans or bedrock, or matches calculations from soil carbon models. Multiple cores may be well-mixed into a single composite sample for analysis. Known volumes of soil from the cores must be sieved to remove rocks, pebbles, and coarse fragments, and then the remainder dried (5 days at 45^{o}C or equivalent) and weighed to determine bulk density. Soil auger
Frequency of monitoring/recording	At the end of the monitoring period for measured approach projects, or, for modeled approach, after a desired monitoring period for re-validating the chosen soil carbon model on the basis of its ability to predict changes in soil carbon during the monitoring period.
QA/QC procedures to be applied	However, the depth used in calculating SOC after Y years of project activities must be adjusted to account for changes in bulk density such that $DEPTH_{m,j,Y}$ x $BULK_{m,j,Y}$ = $DEPTH_{m,j,0}$ x $BULK_{m,j,0}$. This ensures that equal masses of soil are compared between year 0 and year Y (Hao et al. 2007).
Purpose of data	Calculation of project emissions
Calculation method	

Comments	None

Data/Parameter	$PMSOC_{m,j,L}$
Data unit	t C / ha
Description	Project modeled equilibrium SOC at station j in stratum m
Equations	
Source of data	Project proponent chosen soil carbon dynamic model
Description of measurement methods and procedures to be applied	If project proponents choose to use a model to predict future soil carbon, then the model should use parameters from the project area, stratum, or individual sampling station to predict woody carbon and forecast changes in aboveground woody carbon to the end of the project lifetime. Examples of appropriate models include BGCv2 (Riggs et al. 2015) or GapFire (Ryan and Williams 2011), which account for fire effects on tree mortality against a backdrop of tree growth and woody carbon accumulation over time. For more details, see section 8.1.3.3.2 and Appendix II.
Frequency of monitoring/recording	At verification
QA/QC procedures to be applied	Based on parameter values, measured or otherwise from sampling station *i*, stratum *m*, or the most locally available relevant data sources. In spreadsheets calculating net removals to soil carbon, all parameters should transparently reference source data. Model may be calibrated to local conditions and assessed at validation and found to meet criteria for accuracy and uncertainty. See details in Appendix II.
Purpose of data	Calculation of project emissions
Calculation method	Model equations must be publicly available and based on previous peer-reviewed publications of the model, subject to posted or published revised versions by the model author(s).
Comments	None

9.2.4 Parameters for Project Soil Carbon Models

If using the modeled approach, the same soil carbon model used to calculate BSOC must be used to calculate SOC expected after Y years of management under the project scenario.

Uncertainties again must be calculated with Monte Carlo simulations (Ogle et al. 2010; Ortiz et al. 2011).

Model input parameters must be tracked at each sampling station, to allow the chosen soil carbon model(s) to be most responsive to variation in major inputs to the model. The model must predict SOC density from the parameters measured and used in the model.

At verification, the project proponent must provide a list of parameters for each station under the project scenario in year y, using the the latest version of the VCS table format for each. **These parameters will vary among models, so an exhaustive list cannot be provided.** The list below is not required; it is a list of parameters that are likely to be required. However, each parameter in the model used to generate the estimated **change in soil carbon density at each sampling station** must be listed, along with its uncertainty based on a 95 percent confidence interval, so that uncertainty calculations, following the Monte Carlo procedures in 8.4.2 may be verified. For example:

Data/Parameter	$MAP_{m,Y}$
Data unit	mm/year
Description	Mean annual precipitation in stratum m over the project crediting period Y years
Equations	
Source of data	Precipitation maps or nearby weather stations
Description of measurement methods and procedures to be applied	A key variable that affects a number of processes driving SOC
Frequency of monitoring/recording	Annually if obtained from government sources or local weather stations, Daily if collected on the project area
QA/QC procedures to be applied	Data should be obtained from government sources or local official weather stations, or, if not available, from weather data collected on the project area.
Purpose of data	Calculation of project emissions
Calculation method	
Comments	None

Data/Parameter	ST j,m,Z
Data unit	°C
Description	Soil temperature at station j in stratum m in month Z
Equations	
Source of data	Measured in project area
Description of measurement methods and procedures to be applied	Must be measured with a digital thermometer with probes inserted to at least ½ the depth at which SOC will be sampled (i.e., to 10 cm if soil will be sampled and modeled to 20 cm (Ogle et al. 2010; Piñeiro et al. 2006)
Frequency of monitoring/recording	At least monthly
QA/QC procedures to be applied	Procedures must follow those in Norman et al. (1992) and Rajan et al. (2013)
Purpose of data	Calculation of project emissions
Calculation method	
Comments	None

Data/Parameter	*GIj,m,z*
Data unit	dimensionless
Description	Mean annual grazing intensity at station j in stratum m in year y
Equations	
Source of data	Measured in project area
Description of measurement methods and procedures to be applied	Measured at each sampling station at least twice each growing season prior to verification by comparing clipped biomass at least at the end of the growing season, or more frequently for some models, inside and outside small (1 m2) fences. GIm = 1 – (biomass outside/biomass inside). Biomass is clipped, dried at 25 – 50 oC, and weighed.

Frequency of monitoring/recording	Must be at least twice per year, but preferably monthly, particularly in tropical project areas where plant growth can occur in any month
QA/QC procedures to be applied	Samples should be dried in a professional drying oven for 3 days at 45-60oC or be air-dried in sunshine for 4-7 days to a constant mass, following McNaughton (1985), Ritchie (2014), and Ritchie et al. (1998).
Purpose of data	Calculation of project emissions
Calculation method	
Comments	None

Data/Parameter	D
Data unit	years
Description	Years required to achieve SOC equilibrium
Equations	
Source of data	SOC model
Description of measurement methods and procedures to be applied	SOC models applied must meet with the modeling requirements described in Section **Error! Reference source not found.**.
Frequency of monitoring/recording	Once
QA/QC procedures to be applied	N/A
Purpose of data	Calculation of project removals
Calculation method	Calculated from chosen project model at year L = project lifetime
Comments	None

In addition, soil carbon models for the project scenario will likely use project burned area in stratum *m* in season *b* in year *y*, $PBA_{m,b,y}$ or the frequency of fire (proportion area burned) in stratum m during year *y*, and initial $SOC_{m,j,0}$.

9.2.5 Parameters for Woody Biomass Carbon Stock Changes

The two principal parameters are the is the aboveground woody biomass in matched pair project polygons on the project area and matched control plots off the project area but with

with similar baseline conditions as the project polygons. Uncertainty is expressed as 95% percent CI/mean for each recorded difference in biomass at each of the permanent sampling stations.

Data/Parameter	$WB_{m,j,F}$
Data unit	kg/ha
Description	Aboveground woody biomass at the project start or the year of last verification at station j and stratum m in the beginning of the monitoring period (year F), including the case where F = 0
Equations	
Source of data	Measured in permanent sampling plots
Description of measurement methods and procedures to be applied	Circular quadrats centered at each permanent sampling station j must be sampled for number and diameter at breast height (dbh) of each woody stem within a specified diameter. Radius must be > 5 cm depending on woody stem density, with smaller radii appropriate for more dense woody vegetation.
Frequency of monitoring/recording	During the beginning of the monitoring period
QA/QC procedures to be applied	Procedures must follow those detailed in MacDicken (1997).
Purpose of data	Calculation of project changes in carbon stocks of woody biomass. These data are used either to calibrate remote-sensing based models used to determine project removals, or to quantify losses of woody carbon stocks due to clearing or fire to increase SOC.
Calculation method	
Comments	None

Data/Parameter	$AWB_{m,j,y}$
Data unit	kg/ha
Description	Aboveground woody biomass at station j and stratum m in year Y at the end of the monitoring period
Equations	
Source of data	Measured in project area at permanent sampling stations
Description of measurement methods	Circular quadrats centered at each permanent sampling station j must be sampled for number and dbh of each woody stem within a specified

and procedures to be applied	diameter. Radius must be 5-50 m depending on woody stem density, with smaller radii appropriate for more dense woody vegetation.
Frequency of monitoring/recording	Once at the end of the monitoring period
QA/QC procedures to be applied	Procedures must follow those detailed in MacDicken (1997).
Purpose of data	Calculation of project emissions
Calculation method	
Comments	None

Data/Parameter	$PRSAWB_{m,jpY}$, $PRSAWB_{m,p,F}$
Data unit	kg biomass/ha
Description	Aboveground woody biomass in the year prior to the monitoring period (for example, at the beginning of the project (y = 0) or final year of the previous monitoring period, F) at paired polygon p in stratum m and in year Y at the end of the monitoring period
Equations	
Source of data	Measured in project area at permanent polygons
Description of measurement methods and procedures to be applied	Calibrated remote-sensing methods must be used, either with high resolution spectral satellite imagery, such as from Sentinel-2, Worldview-3, Quickbird.
Frequency of monitoring/recording	In the last year F of the previous monitoring period or in the case of F = 0, at the start of the project. Also in year Y at the end of a montoring period
QA/QC procedures to be applied	Data to be stored off-site (Cloud or data storage service), on paper, and in storage media directly controlled by the project proponent, including hard drives, flash drives, etc. Field crews will be trained and use tablets or other digital data entering devices for entering information so that data is automatically uploaded to the off-site storage as soon as wireless connections are available. This avoids errors in transcribing data. Digital data will later be printed for archival against loss of access to digital storage media (drives or offsite online storage)

	Procedures must follow those detailed in MacDicken (1997).
Purpose of data	Calculation of changes in woody biomass carbon stocks
Calculation method	N/A
Comments	None

Data/Parameter	CRSAWBm,jpY, CRSAWBm,p,F
Data unit	kg biomass / ha
Description	Aboveground woody biomass in the year prior to the monitoring period (for example, at the beginning of the project (y = 0) or final year of the previous monitoring period, F) at control plot polygon p in stratum m and in year Y at the end of the monitoring period
Equations	
Source of data	Measured in project area at permanent polygons
Description of measurement methods and procedures to be applied	Calibrated remote-sensing methods musr be used, either with high resolution spectral satellite imagery, such as from Sentinel-2, Worldview-3, Quickbird.
Frequency of monitoring/recording	In the last year F of the previous monitoring period or in the case of F = 0, at the start of the project. Also in year Y at the end of a montoring period
QA/QC procedures to be applied	Data to be stored off-site (Cloud or data storage service), on paper, and in storage media directly controlled by the project proponent, including hard drives, flash drives, etc. Calibration will require field measurement of AWB (see section 8.2.3). Field crews will be trained and use tablets or other digital data entering devices for entering information so that data is automatically uploaded to the off-site storage as soon as wireless connections are available. This avoids errors in transcribing data. Digital data will later be printed for archival against loss of access to digital storage media (drives or offsite online storage) Procedures must follow those detailed in MacDicken (1997).

Purpose of data	Calculation of changes in woody biomass carbon stocks
Calculation method	N/A
Comments	None

9.2.6 Parameters for Leakage

Data/Parameter	DNc,x
Data unit	head
Description	Number of livestock of each category c that were outside the project area (outside the fence defining the boundary of the project area, or, in the case of open grazing lands e.g. pastoralist areas, beyond 2 km from the mapped project area boundary on day x)
Equations	
Source of data	Measured
Description of measurement methods and procedures to be applied	Determined from records of livestock distributions, as recorded from interviews with grazing managers, coordinators, herders, or other administrative staff. For additional details see Section 9.3.3.
Frequency of monitoring/recording	Monthly
QA/QC procedures to be applied	Records should be kept as paper and electronic copies
Purpose of data	Calculation of leakage
Calculation method	N/A
Comments	None

Data/Parameter	d
Data unit	days
Description	Total number of days livestock were off the project area
Equations	

Source of data	Measured
Description of measurement methods and procedures to be applied	Based on records of livestock numbers and their distribution on and off the project area, based on interviews of grazing managers, coordinators, herders, or other administrative staff. For additional details see Section 9.3.3.
Frequency of monitoring/recording	Weekly to monthly
QA/QC procedures to be applied	Records should be kept as paper and electronic copies, with at least one electronic copy kept off the project as an online database
Purpose of data	Calculation of leakage
Calculation method	N/A
Comments	None

Data/Parameter	r
Data unit	proportion
Description	Annual rate of increase in animal production on the project area during the baseline period
Equations	
Source of data	Measured As determined in/for the project area; or a default value of 0.025 from verra Methodology VM0047 may be used
Description of measurement methods and procedures to be applied	Calculated from trend in animal numbers over the 10-year baseline period, BNc,y
Frequency of monitoring/recording	Estimated at the start of the project
QA/QC procedures to be applied	Records should be kept as paper and electronic copies, with at least one electronic copy kept off the project as an online database
Purpose of data	Calculation of leakage
Calculation method	N/A
Comments	None

Data/Parameter	IS
Data unit	proportion
Description	Protportion of foregone production supplied off the project area
Equations	
Source of data	Measured
Description of measurement methods and procedures to be applied	Based on records of livestock numbers and their distribution off the project area following project activity reductions in animal numbers, based on interviews of producers, direct counts, or government censuses. For additional details see Section 9.3.3. As determined in/for the project area; default from Verra Methodology VM0047 = 0.7
Frequency of monitoring/recording	Weekly to monthly
QA/QC procedures to be applied	Records should be kept as paper and electronic copies, with at least one electronic copy kept off the project as an online database
Purpose of data	Calculation of leakage
Calculation method	N/A
Comments	None

Data/Parameter	MNy
Data unit	Animal-days
Description	Mitigated temporary animal displacement off the project area but used land by documented agreement with landholders and followed movements similar to the project activity
Equations	
Source of data	Measured
Description of measurement methods and procedures to be applied	Based on records of livestock numbers and their distribution on and off the project area, locations and numbers recorded by project staff, based on interviews of grazing managers, coordinators, herders, or other administrative staff. For additional details see Section 9.3.3.
Frequency of monitoring/recording	Weekly to bi-weekly

QA/QC procedures to be applied	Records should be kept as paper and electronic copies, with at least one electronic copy kept off the project as an online database
Purpose of data	Calculation of leakage
Calculation method	N/A
Comments	None

9.3 Description of the Monitoring Plan

9.3.1 Sampling Design

The requirements for sampling design of the permanent sampling stations and their division among strata is described in detail in Appendix I.

9.3.2 Impact of Project Activities

Additionality of greenhouse gas reductions arises from the implementation of new management activities, and it is important for the project proponent to monitor the effectiveness of these new activities. Activities fall principally into three major categories: (1) manipulating animal numbers and grazing intensity, (2) managing fire, (3) changing plant species composition and/or lignin and cellulose content.

9.3.3 Animal Numbers

The different methods of animal censuses are reviewed by Seber (1992). The preferred methods are:

1) *Ownership records* in cases where individual records exist for each animal owned by the project proponent or participants. This is the most accurate measure of animal numbers but is likely to only be possible in developed countries where such records can be created and maintained.

2) *Corral counts*, in which all known corrals or "bomas" where animals are kept at night are identified to category c and counted. The advantage of this method is that it allows a total census as long as all corrals can be located and censused. This may be the superior method for censusing animals kept by pastoralists in less developed countries. Care must be taken to census at times when animals are not being herded long distances to find new pasture or water, as the census may significantly underestimate animal counts. 95 percent confidence intervals may be estimated by repeated counts, comparison of counts among different observers, or subsampling methods like bootstrapping (Tsay and Chao 2001).

3) *Ground transect counts*, whereby transects are walked or driven and the number of animals of each category c, at distances measured with rangefinders, are counted. The

area sampled by transects (length by mean observation distance) must cover at least 20 percent of the project area (Seber 1992) to avoid unacceptable variance and uncertainty. Counts must be converted to density and multiplied by area to estimate total animal numbers in each category and their 95 percent confidence intervals by using the program DISTANCE (Thomas et al. 2010). Transects must be sampled in at least four years of the ten prior to the project start and at least twice per year during the project crediting period Y years. The advantage of this method is that it may be applied to wildlife or to livestock censuses in regions where livestock are not sedentary. The disadvantage is that animals are often aggregated across the landscape, which may greatly increase the variance of the estimate, animals counted must be extrapolated to get totals for the project area, and accurate classifications of animals into categories may be inaccurate.

4) *Human surveys*, in which animal owners are interviewed about animal numbers of each category, kept in their corrals in the past. At least 30 individuals or 10 percent of the total animal holders in the project area, whichever is greater, must be interviewed. The advantage of this method is that more detail about breeds and weights may be incorporated into the determination of categories and estimation of methane emissions. The disadvantage is that the subsample of animals owned by the people interviewed must be extrapolated to encompass the project area, with accompanying uncertainty.

5) *Aerial surveys* in which animals of each category are counted from aerial photographs. This is a popular method among governments who are satisfied with broad surveys, but typically the uncertainty in aerial surveys is too large to be used with daily methane emissions, which are already plagued with relatively large uncertainties. Typically, aerial surveys only work for cattle or other similarly large animals (e.g., camels and horses), as sheep and goats are usually too small to be differentiated by species, sex or age from the air. Also, uncertainties for aerial surveys may be prohibitive, as they often exceed 50% (Seber 1992).

9.3.4 Grazing Intensity

The project proponent may need to measure aboveground plant biomass at least semi-annually to determine the impacts of grazing on vegetation throughout the project area. This parameter is not required, as it is used only in some SOC dynamic models, the parameter $GI_{m,j,y}$ represents the percent difference in standing crop between grazed and ungrazed (fenced) vegetation. It may be measured at all permanent sampling stations by comparing aboveground plant biomass, $APB_{j,m,y}$ at each station with biomass inside small fences (0.67 – 2 m^2). Herbaceous and shrub biomass must be clipped from three or more small quadrats at each station and from two or more small (0.67 - 2 m^2) temporary fenced quadrats (utilization cages). Grazing intensity (GI) is 1 – (biomass unfenced/biomass fenced) (McNaughton 1985). Cages must be moved after clipping to ensure that the station measures grazer use of plant production over each season or portion of a season. It may also be measured using calibrated satellite imagery (with at least $R^2 > 0.60$ between the satellite index and measured biomass on the ground) by comparing vegetation indices, such as NDVI or EVI (Feng and Zhao 2011; Huete et al. 2002), between ungrazed and grazed pixels paired to have similar soil types, precipitation, and other variables.

9.3.5 Burned Area (Updated from 'Fire Frequency in V1"

Baseline area burned ($MBA_{m,b}$) and project proportion of area burned during the project crediting period Y requires demonstration of the occurrence and area covered by fires over a period of 10 years for the baseline and Y years for the project scenario. Acceptable information sources include aerial photographs or interpreted satellite images with a resolution (pixel length in m) smaller than 0.5 percent of the square root of the total project area (in m^2) (De Santis et al. 2010; Dempewolf et al. 2007). An example method is Dempewolf's et al. (2007) algorithm, now employed as MODIS Burned Area images dating back to 2000. These images use red and infra-red spectral information from 15-day composite images, which eliminate clouds and shadows, from MODIS satellites[22] to calculate a BAI, or burned area index that provided 85-95 percent accuracy in classifying image pixels as burned or unburned in East African grassland and savanna.

Other methods of image interpretation, particularly aerial photographs, may be used. Any method must be tested by comparing pixels in classified images with observations of burned or unburned during the same time window in the permanent sampling stations. Valid interpretation methods must commit less than 12 percent combined omission and commission errors (Dempewolf et al. 2007).

9.3.6 Plant Species Composition

A key input variable affecting soil carbon dynamics and soil carbon models is species composition, as management practices to restore soil carbon will likely do so in part by changing plant species composition (Conant et al. 2001; Derner and Schuman 2007; Izaurralde et al. 2006). Replacement of woody shrubs or annual grasses that dominate under baseline conditions with perennial grasses with deep root systems under the project scenario can lead to rapid carbon sequestration. Tracking plant species composition may be done by measuring aerial cover of the four most dominant species each of grasses, herbs (dicotyledonous plants, wildflowers), and woody plants. Such data can show shifts as a consequence of new management activities.

9.3.7 Plant Lignin and Cellulose

Shifts in species composition may be accompanied by shifts in plant chemical composition that greatly affect calculations of some soil carbon models and measurable soil carbon sequestration. SOC is often closely related to inputs of these forms of carbon because they resist microbial decomposition. Plant cellulose and lignin (MAPLC) may be measured by either: 1) the Van Soest method of sequential digestion of ground plant material (clipped during the measurement of aboveground plant biomass (APB)) in acid detergent and sulfuric acid (Jensen et al. 2005) in a professional laboratory, or 2) with infra-red (IR) spectrometers calibrated to project area plants and soils.

9.3.8 Soil Organic Carbon

A critical measurement is initial SOC which is necessary in establishing the baseline SOC in the measured approach and validating the chosen soil carbon dynamic model in a modeled approach. Multiple stations must be sampled within each stratum so as to determine a 95% percent confidence interval. Some models only quantify changes in SOC to specific depths, (e.g., CENTURY only predicts SOC to a depth of 20 cm (Feng and Zhao 2011; Piñeiro et al. 2006), and if using a modeling approach with a restricted depth, the project proponents must measure depth that matches that of the model. If using a measured approach or a model that allows different soil depths to be used, and appreciable soil carbon stocks occur below 30 cm (Knops and Tilman 2000), then proponents are justified in sampling deeper in the soil profile, even to a depth of 1m. Known volumes of soil from the cores must be sieved to remove rocks, pebbles, and coarse fragments, and then the remainder dried (5 days at 45^{o}C or equivalent) and weighed to determine bulk density (Mg/m^3) (Hao et al. 2007).

If an IR spectrometer is to be used, the project proponent must show all calibration data in a table with spectral emissions and measurements of soils or plants and graphs showing the regressions of spectral data against measurements.

9.3.9 Ex Ante Leakage and Other Emission Sources

Leakage is mainly possible from net transfers of livestock out of the project area, which is not allowed by the applicability conditions but nevertheless must be monitored by inventorying livestock shipping depots and from censuses and interviews with inhabitants of the project area. Close monitoring and census efforts are especially needed during dry seasons or other periods when there may be strong motivation to move animals off the project area. Animal censuses must be timed to coincide with the greatest risk of animal movement to have the greatest chance to track any possible leakage. The possible but unlikely source of new emissions as a result of the project is the increase in the use of fossil fuels during vehicle and airplane use associated with management activities. These may be tracked with mileage logs in all project and associated vehicles and converted with the most recent IPCC Guidelines for National Greenhouse Gas Inventories emission factors as stratified by the type of vehicle and fuel type (e.g., diesel, gasoline, kerosene), to determine whether fossil fuel use approaches being a significant greenhouse gas source associated with project activity.

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APPENDIX 1: TESTING THE SIGNIFICANCE OF CARBON POOLS AND GHG EMISSIONS

This appendix outlines procedures for the determination of insignificant emission sources and/or changes in carbon pools.

Individual carbon pools and emissions sources may be neglected if the relative contribution of the decreases in a carbon pool, or increases in an emissions source is less than 5 percent of the sum total of all decreases in carbon pools and increases in emissions less than 5 percent of carbon dioxide removals (or 1% for projects with annual removals > 300,000 tons CO_2e), whichever is smaller.

$$RC_{Es} = \frac{Es}{\sum_{s=1}^{S} Es}$$

Where:

RC_{Es}	=	Relative contribution of each source *s* to the sum of project and leakage GHG emissions
Es	=	GHG project emissions, leakage emissions and decreases in carbon pools s
s	=	1, 2, 3, …, *S* sources of project and leakage GHG emissions, and decreases in carbon pools

Rank the decreases in carbon pools and emissions in descending order of their relative contributions RC_{Es} and order them according to their ranks (i.e., the lowest emission gets the highest rank and occupies the last position in the ordered sequence of emissions).

Calculate the cumulative sum of the relative contributions *RCEs* beginning with the lowest rank. Cease the summation when the cumulative sum equals or exceeds the threshold of 0.95.

The GHG emissions, possible decreases in carbon pools and leakage emissions not included in the summation are considered insignificant where their sum is lower than five percent of carbon dioxide removals. Otherwise, the procedure described above must be continued beyond the threshold of 0.95 until the above condition is met.

APPENDIX 2: RECOMMENDATIONS FOR STRATIFICATION

The primary goal of the distribution of stations must be to represent conditions and activities contributing to **changes in carbon stocks** on the project area, and reduce variability in the project area. It is important to note that, in this methodology representation is of expected changes in soil carbon stocks between two sampling times (e.g., project start to year *Y*) at each sampling station. Representation is not of mean carbon stocks, as the methodology does not compare mean carbon stocks but rather the mean pairwise difference in carbon stock at each sample point.

Thus, using the latest version of the VM0042 Soil Sampling and Analysis (SSA) Handbook , the project proponent may classify the area by past management practices and preliminary information about soils (such as from a soils map) and climatic conditions (such as from areas that are similar in aboveground productivity, or from rainfall maps). This step is equivalent to stratification in an afforestation / reforestation project but is focused on factors related to soil carbon sequestration, fire frequency, and animal distribution and management. The purpose of stratification is to reduce the uncertainty in quantified reduction or removals.

This will produce *s* strata within which baseline and project emissions are calculated, soil carbon changes and methane emissions will be monitored, and past (baseline) and proposed project management activities have been (are) implemented.

As an example, a project might be subdivided into five areas of different soil type and/or precipitation as seen in Figure S1. The sampling design would then feature eight strata, one for each combination of management activity, soil type, and precipitation or water availability.

Once each stratum is defined and mapped and the total number of sampling stations determined, then a representative number of sample points, z_m, are chosen within each stratum *m*. The number of points per stratum will depend on which stratified sampling method is used. Where SOC exhibits similar variability among strata (i.e., coefficients of variation (standard deviation/mean) differ by less than 40% in areas with different soil, vegetation, or management practices), the number of stations per stratum must be proportional to the proportional area of each stratum in the project area. This is the most likely scenario under the expectation that strata for a project are selected to ensure a low uncertainty (10 percent standard error) within each stratum. For example, in a project with three strata, A, B, and C that represent 50 percent, 40 percent and 10 percent respectively of the total project area and the project area requires 100 sampling stations, then 50, 40, and 10 stations must be placed randomly within each of strata A, B, and C, as shown in Figure S2 below. This is the case of proportional allocation, which the number of stations is allocated to each stratum on the basis of its proportion of the total project area.

A2.1 Situations When Stratification Might Not Reduce Uncertainty

This section provides guidance about how best to determine changes in carbon pools and emissions over time. In most cases, methodologies and project proponents are interested in comparing average measures of pool sizes or emissions at two or more points in time. In natural landscapes, variation in soils, plant species composition and human activity may produce large differences in estimates of pool sizes and emissions. Traditionally, uncertainty in these estimates are thought to be reduced by stratifying landscapes according to these different conditions. However, this report demonstrates that such an approach may or may not be desirable, given the time and financial cost of sampling and sample processing.

An alternative method of accounting is to quantify carbon pools and/or emissions at individual sampling points throughout a project area and then tracking the difference in pools and emissions **at each sampling point.** In this case, the project activity generates a **mean difference** (rather than a difference in means) that accounts only for variation in the change in carbon pool rather than variation in the carbon pool. Calculations below illustrate that

1) Unless the mean carbon pool or flux from one stratum is more than 2x that of the other, overall uncertainty in the carbon pool estimate will likely be higher if samples are stratified than if not.
2) Uncertainty in the mean difference will be much lower than uncertainty in the difference between means,
3) Large differences in mean carbon pools between two sets of environmental conditions may suggest stratification, but such differences in pools may not transfer into differences in carbon pools over time across sample points.
4) Minimum sample size requirements, for the same standard deviation in the data, are > 10x higher for achieving equivalent uncertainty for the difference between means than for the mean difference in a carbon pool.

Consider the following example data (Table 2-1).

Table 2-1. Comparison of two methods of estimating a change in carbon pool: A) difference between means of the from 10 samples within each of two strata across two times or B) estimating the mean difference in carbon pool across the 10 sample points.

	Example data											
	Time 1	Time 2	Difference				Time 1	Time 2	Difference			
Stratum 1	30	32.5	2.5			**Stratum 2**	51	52.8	1.8			
	35	36.7	1.7				54	56	2			
	15	17	2				44	46.1	2.1			
	33	34.8	1.8				70	72.9	2.9			
	31	33.2	2.2				56	57.3	1.3			
	28	31	3				62	65	3			
	15	18.5	3.5				39	43	4			
	42	43.7	1.7				45	46.5	1.5			
	50	51.9	1.9				18	20.8	2.8			
	38	41.2	3.2	Mean Difference	Difference in Means		49	50.6	1.6		Mean Difference	Difference in Means
Mean	31.7	34.05		2.35	2.35		48.8	51.1			2.3	2.3
SE	3.444964	3.358877		0.210422855	3.444964119		4.459197736	4.427063			0.268741925	4.443130485
Uncertainty	17.8%	16.2%		14.7%	240.4%		15.0%	14.2%			19.2%	316.8%

The measured carbon pool at time 1 is nearly 50% (and significantly, $P < 0.001$) larger in stratum 2 than in stratum 1, suggesting grounds for stratification. The uncertainties within strata are within reasonable bounds (14-17%). The pooled uncertainty for the estimate of the carbon pool is 15.2%. When the pool is measured at time 2, the estimate of the pool exhibits similar uncertainty.

The difference in the carbon pool at each sample point averages to the same value as the difference between Time 1 and Time 2 means, thus either calculation yields the same estimate of change in the carbon pool. However the uncertainty in the **mean difference** is substantially smaller (14.7 – 19.2%) than the uncertainty in **the difference between means** (240-316%). In addition, the estimated **mean differences** are virtually the same for the two strata, thus suggesting no basis for stratification if changes in the carbon pool is calculated as a mean difference.

Furthermore, estimating either the mean difference or the difference between means without stratification, yields approximately the same estimate for change in the carbon pool, but lower uncertainty for both ways of calculating the change in carbon pool (Table 2-2). Thus, if reducing uncertainty in the change in the carbon pool is the goal, then the project should not stratify its monitoring design. Further calculations suggest that the difference in mean carbon pool in this example would have to be 2x or higher in Stratum 2 as compared to Stratum 1 before the pooled uncertainty in the stratified estimates would be less than the uncertainty for the unstratified samples.

Table 2-2. Estimates of change in the carbon pool over Y years *without stratifying, that is across all 20 sample points.*

	Stock at y=0	Stock at y=Y	Mean Difference	Difference in Means
Mean	40.25	42.575	2.325	2.325
SE	3.371611	3.337505	0.166208	3.354558
Uncertainty	13.7%	12.9%	11.7%	236.6%

The difference in uncertainty between the two methods of calculating the change in carbon pool implies a difference in the sample size needed to achieve a threshold level of uncertainty. For the example above, estimating change from the difference between means requires 10 x the samples to achieve the same uncertainty as estimating the mean difference in carbon pools (Fig. 2-1).

Figure 2-1. Estimated uncertainty in the above example dataset for the difference between means (blue) and the mean difference (orange). Note that the mean difference carries less than 10% uncertainty at < 100 samples, while the difference between means still exceeds 100% at 100 samples and would exceed 30% even at 800 samples.

For projects considering stratification and uncertainty, stratification likely makes sense only if the means in the strata are 2x or more apart, with the necessary difference increasing with increasing variability around the means.

A2.2 Test for the Need for Stratification

If potential strata such as soils, precipitation, and management have been identified (see hypothetical strata in Figure 2-2) and then tested by a k-factor means or other cluster analysis (see section Appendix 2 section 2.1), the resultant mean carbon stocks associated with each potential stratum factor will have an associated standard error (SE_i) that can be used to assess uncertainty (margin of error for each stratum *I*, ME_i) at a 90% Confidence Interval (as required by the latest version of the Verra Methodology Requirements version 4.4 and later)

$$ME_i = 1.64 * SE_i / \mu_i \qquad \text{(App 2.3.1)}$$

Where

1.64	=	value of *t* for the 90% Confidence Interval at infinite sample size
μ_i	=	estimate of mean carbon stock (metric tons or metric tons ha^{-1})

Following the distribution of sample points and measurement of initial carbon stocks, ex ante estimates of change in carbon stocks at each sample point, based on local inputs, over *Y* years of an assessment period can be estimated **at each sampling station** using a modeling approach or estimates from literature review(s) for different local inputs (e.g., mean annual precipitation, soil texture, mean annual temperature, etc.)

From the estimates of margin of error for each stratum, calculate the pooled margin of error, PME_U for the stratified samples:

$$PME_s = \left[\frac{\sum_{i=1}^{s} \left(\frac{1}{Z_m}\right) \times \sum_{j=1}^{Z_m} \Delta MCS_{m,j} \times {ME_m}^2}{\frac{\sum_{j=1}^{Z_m} \Delta MCS_{m,j}}{Z_m}} \right]^{1/2}$$

(App 2.3.2)

Where

PME_S	=	Pooled margin of error across strata
$\Delta MCS_{m,j}$	=	expected difference in carbon stock at point *j*, from chosen carbon stock model
Z_m	=	number of sample points in stratum *m*
S	=	number of strata

ME_m = margin of error in mean expected difference in carbon stock in stratum *m (see equation App2.3.1).*

Step 2

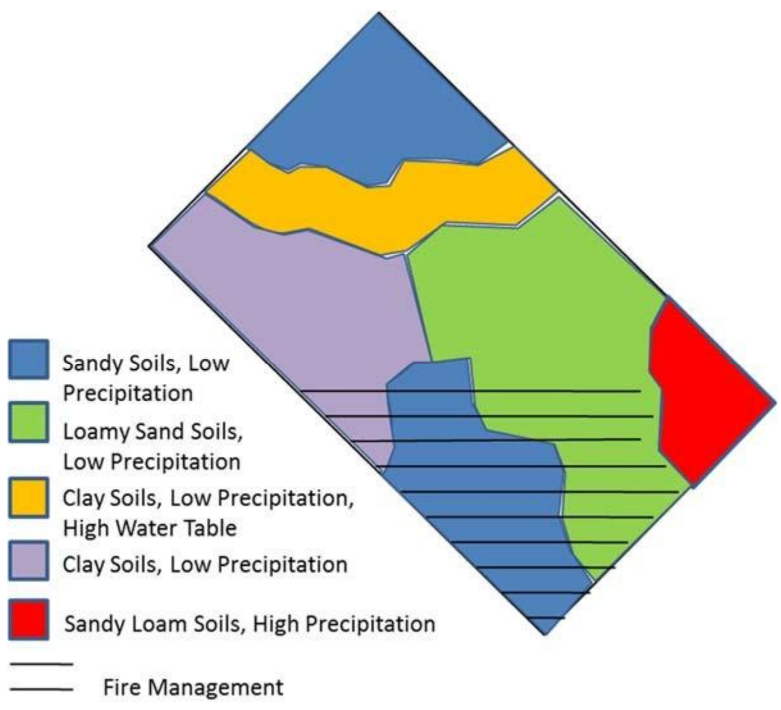
Proponents should calculate the margin of error for the unstratified sample, ME_U. based on all *n* sample points in the project area.

Step 3

Proponents may avoid using stratification if

$ME_U < PME_S$

Figure 3. Hypothetical landscape with eight strata subject to different management practices



Alternatively, the best possible stratification of the project area, resulting in the least uncertainty, may still feature certain strata that exhibit much higher variability (> 40% difference in coefficient of variation) in SOC than others. In this case, "optimum" or disproportionate allocation of stations may be most appropriate. Where a disproportionate application is applied, strata receive a number of sampling stations proportional to their coefficient of variation rather than their proportional area. In the example, hypothetical strata A, B, C might receive 20, 20, and 60 percent of stations, respectively if SOC in stratum C is three times more variable (three times higher coefficient of variation), regardless of their proportional areas. As an example, Figure 2-3 shows the disproportionate allocation of 25 sampling stations in the hypothetical project area shown below. In this case the high precipitation stratum and the clay soils with a high water table are three times more variable than other strata, and thus receive 6 stations, as opposed to two, in Figure 2-4.

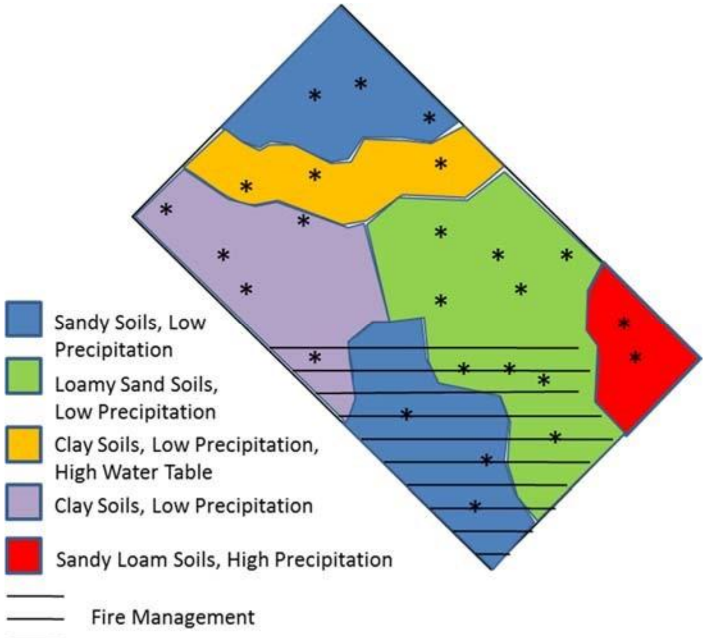


Figure 2-3: Proportional Allocation of Sampling Stations (Stars) Among the Eight Strata in the Hypothetical Project Area in Figure 2

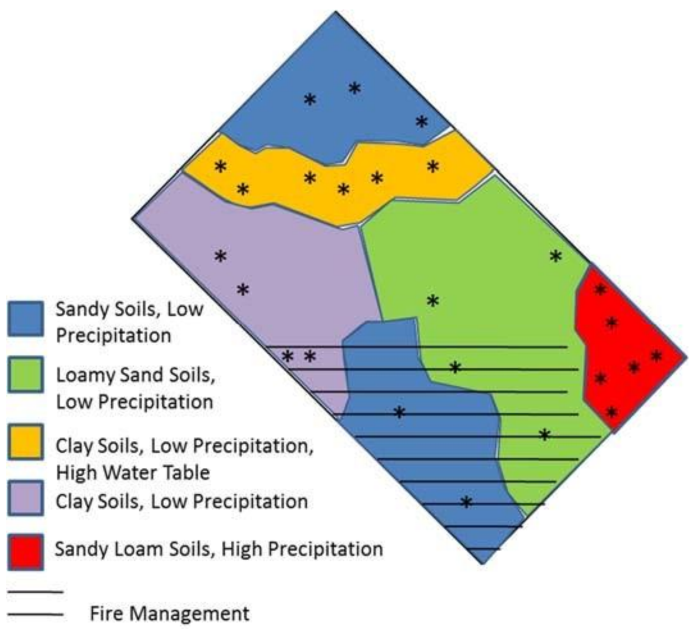


Figure 2-4: Optimal or Disproportional Allocation of Sampling Stations (Stars) Among the Eight Strata of the Hypothetical Project Area in Figure S1.

APPENDIX 3: MODEL ASSESSMENT AND CALIBRATION

To employ a Modeled Approach in calculating removals to soil and aboveground woody plant carbon stocks, project proponents must use a carbon stock dynamic model that meets the following criteria for determining its quality and validity for use in linking activities to changes in carbon stocks. The model must be:

1) 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 of how the model functionally represents carbon stock dynamics must be accessible. Providing the source code or an API for independent replication of calculations is not necessary;
2) Shown in peer-reviewed scientific studies to successfully simulate changes in SOC and trace gas emissions resulting from changes in agricultural management included in the project description;
3) Independent reviewers, such as a Validation and Verification Body, must be independently capable of implementing model runs in order to replicate project calculations. This includes clear versioning of the model used in the project, stable software support of that version, as well as fully reported sources and values for all parameters used with the project version of the model.
4) New model versions, not published in peer-reviewed journals, can be used in projects. These versions incorporate accumulating feedbacks from confrontation with data and updates should be made or acknowledged by the model author(s). Versions should be clearly indicated, with associated metadata justifying model changes and any new parameter values and maintained on a university, government, Github or other public site.

Further recommendations for model integrity are provided in VMD0053 Model Calibration, Validation, and Uncertainty Guidance for the Methodology for Improved Agricultural Land Management v 2.0.

The chosen model must be assessed for accuracy and precision at least once with an independent set of data other than that originally used to construct the model in a peer-reviewed journal. For example, SNAPGRAZE (Ritchie 2020), CENTURY (Feng and Zhao 2011; Paustian et al. 1992; Piñeiro et al. 2006), EPIC (Izaurralde et al. 2006; Williams et al. 1989), and Hurley Pasture (Arah et al. 1997; Thornley and Cannell 1997) are four models that incorporate grazing and/or fire, among others, as factors determining SOC. Likewise, models of aboveground woody biomass carbon, AWBC, dynamics in project areas subject to fire, such as BGCv2 (Riggs et al. 2015) or GapFire (Ryan and Williams 2011) determine the number of trees or saplings of different size (and thus carbon content) that persist in a landscape with different fire regimes.

One or more of these or other candidate models must be assessed for accuracy independently (e.g., preferably with data collected from the project area or nearby areas with similar habitats and drivers of carbon stocks). However, proponents can also use data from peer-reviewed sources or other reputable but *non peer-reviewed* sources such as project reports or data collected by government agencies, non-governmental organizations, and studies conducted on behalf of the project proponent (e.g., by a consultant) *as long as the sources are clearly documented.* The chosen model version is then tested to demonstrate it is appropriate for use in the project area. Data should be from the same IPCC climate zone or justified by the project proponent to be from a similar habitat and land use.

The model must demonstrate the ability to predict:

1) initial carbon stocks in different subareas (strata) within the project area if such strata are employed (see below). This analysis assumes that past practices and their timing are known and have been in place long enough to influence carbon stocks, and that the influence of these historical conditions can be captured in model coefficients and input parameters. Proponents assessing carbon stock dynamic models must describe the temporal pattern of activities and conditions assumed to have occurred in the past that would lead to a current baseline measurement of the carbon stocks. Prior management activities and environmental conditions, such as animal densities, grazing intensity and timing, fire frequency and intensity, as well as other factors, such as soil texture, climate and plant characteristics that affect decomposition may be represented as parameters in the carbon stock dynamic model.
AND/OR
i) changes in carbon stocks associated with intended project activities. For example, if a project intends to reduce grazing intensity to increase SOC, the model can be assessed by predicting SOC changes from excluding (fencing out) grazers for a known number of years. Such data are likely to be available in the literature, whereas carbon stocks associated with different land use histories may not.

Project proponents must provide a table of parameter values used in the model for the assessment.

Model Calibration

Many process models of changes in carbon stocks require input parameters that are highly variable and/or difficult to measure. Calibration is an effective method of deciding appropriate parameters for a chosen carbon stock model. Calibration typically involves making predictions with the chosen model with a range of input values for one or more parameters and then picking the parameter value(s) that provide the closest match between model predictions and observed carbon stocks or carbon stock changes. The dataset(s) used for matching prediction with observation must be separate and distinct from the data used for model assessment (see below).

If the project proponent chooses to employ calibration of the chosen model, they must follow the procedures and standards for model calibration set forth in section 5.1 of the module VMD0053 *Model Calibration, Validation, and Uncertainty Guidance for the Methodology for Improved Agricultural Land Management* v 2.0.

Model Assessment

Project proponents must use one of two approaches to assess the carbon stock dynamic model of choice for use in the project area.

(1) Proponents may use the entirety of the module VMD0053 *Model Calibration, Validation, and Uncertainty Guidance for the Methodology for Improved Agricultural Land Management* v 2.1.

(2) Proponents may use the following simplified (relative to requirements in VMD0053) protocol for model assessment. This approach does not require sequential measurements of carbon stocks generated by the proposed practice, as does VMD0053, since proponents can assess how past history predicts current carbon stocks.

Accuracy

Project proponents must first assess model accuracy by calculating model bias for either the project as a whole or for individual strata. Assessments at the stratum level will be more likely to fail a test due to small sample size. Bias must be determined using the following formula, equation (App 3.1) (Moriasi et al. 2007).

$$MBIAS = \frac{\sum_{i=1}^{n}(CS^{obs}{}_{i} - CS^{pred}{}_{i})}{\sum_{i=1}^{n} CS^{obs}{}_{i}} \times 100$$

(App 3.1)

Where:

MBIAS = Relative Bias statistic (dimensionless), positive values indicate predicted values > observed, negative values indicate predicted values < observed

$CS^{obs}{}_{i}$ = Observed carbon stock at sampling station *i*

$CS^{pred}{}_{i}$ = Predicted carbon stock at sampling station *i*

n = total number of sampling stations in the project area or stratum

Bias of the chosen model against baseline observed carbon stocks must be between -10% and +10%. In the case that the absolute value of MBIAS > 10% AND that carbon stocks are over-predicted, proponents may use a process of model calibration (see previous section) to adjust model parameters using an independent subset of observed carbon stock data. Such calibration that follows a general procedure may be used and fit the model to data, and then the model may be re-tested with the remaining data.

In the event that the MBIAS < -10%, the model is conservative and can be used without the precision and uncertainty test discussed in the next section.

Precision and Uncertainty

Proponents must compare predicted and observed carbon stocks in a mixed linear model (McCulloch and Searle 2004) with fixed effect observed versus predicted and stratum as a random effect. For the model to be appropriate for use, the mixed model should reveal that predicted mean carbon stock for a stratum is within the 90% Confidence Interval (CI) for the mean observed carbon stocks for each stratum. This amounts to rejecting the hypothesis that the modeled means are the same as the observed means at a threshold of $P < 0.10$ (or setting $\alpha = 0.10$). Further, the 90% CI for model predictions, based on a Monte Carlo or other analytical technique, must overlap the 90% CI for the observed carbon stock for each stratum in the project area. The 90% CI predicted mean carbon stocks **must** be derived from Monte Carlo simulations as recommended by the IPCC or other uncertainty analysis method, justified with peer-reviewed literature or statistical methodological textbooks, appropriate to models with large numbers of parameters. If, for certain strata, the 90 percent confidence intervals do not overlap, then the carbon stock dynamic model must be re-calibrated for those strata by adjusting one or more parameters under the requirements of VMD0053 for calibration in section 5.1, as discussed above. The principal requirement for such calibration is data inputs collected independently from project monitoring and baseline data.

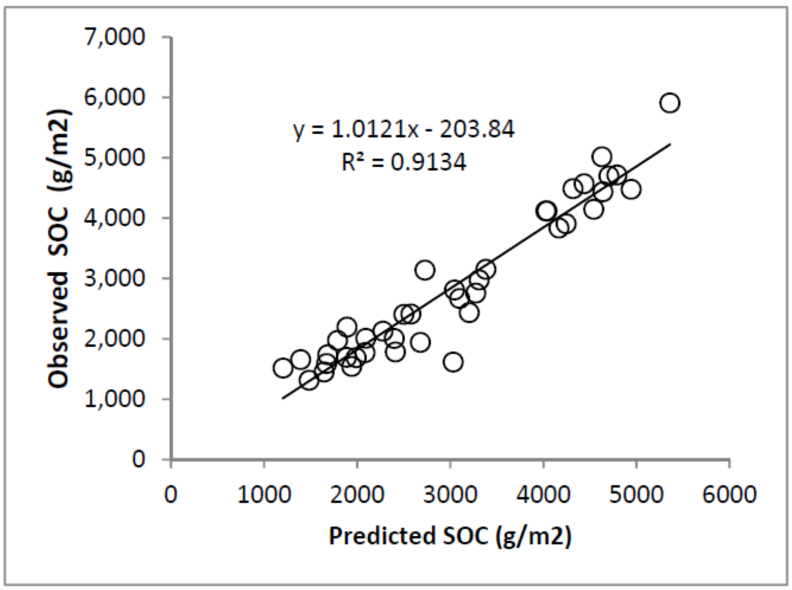


Figure 3-1. Example test of a carbon stock (in this case, SOC) dynamic model using a regression approach by comparing predicted values of the carbon stock with observed values at each of many different sampling points, some chosen to represent the range of carbon stock values across the project area.

The statistics of variation needed to calculate uncertainties for each parameter in the model are also necessary to determine an overall uncertainty in the model calculations of carbon stocks. Total uncertainty of model predictions of baseline carbon stocks, changes in carbon stocks or eventual equilibrium stocks may be determined by an analysis called Monte Carlo simulation (Ogle et al. 2010; Ortiz et al. 2011).

In such a simulation, parameter values are randomly chosen from hypothetical normal distributions with mean equal to the parameter value and the measured standard error around that mean. Once all the different parameter values for the model are generated from the hypothetical distributions, a model prediction is made. This process is repeated 100 or more times to produce a mean model prediction with a 95 percent confidence interval. For baseline carbon stocks, the Monte Carlo simulation would generate an expected value of stocks and a 90 percent confidence interval.

Model Comparison

In some cases, alternative soil carbon models, and/or the same modeling framework with different sets of input parameters, may be appropriate for the same project area and activity (Smith et al. 1997). If so, the project proponent may choose among the appropriate models. To evaluate matched predictions of different models to observed carbon stocks, proponents may choose the model that best predicts current $SOC_{m,j,0}$ or $AWB_{m,j,0}$ at each station in stratum m with the lowest Akaike Information Criterion (AIC) value, as per standard model selection procedures (Burnham and Anderson 2004). Different models may use different numbers of parameters, so AIC is a statistic that measures the amount of variation in observation that is not predicted by a model, corrected for the number of parameters K used in the model to make the prediction:

$$IC = n \times ln\left(\frac{\sum_{i=1}^{n} e_i^2}{\ } \quad \frac{K+1}{n-K-1}\right) \qquad 2 \qquad 2$$

(App 3.2)

Where:

AIC	=	Akaike Information Criterion value
n	=	Number of observations tested, and
e_i	=	Deviation of an observation from its model prediction
K	=	Number of parameters used

Note that models, such as CENTURY (Feng and Zhao 2011; Paustian et al. 1992; Piñeiro et al. 2006), with large numbers of parameters (> 80) require a large number of observations n > K to generate an AIC metric, and such models would also have to generate substantially stronger model fits to observations (higher R^2, lower MBIAS) than much simpler models with fewer parameters, such as the Hurley Pasture model (Arah et al. 1997; Ritchie 2014; Thornley and Cannell 1997) or SNAPGRAZE (Ritchie 2020).

Model Reassessment

The chosen model must be reassessed as soon as changes in SOC may be measured with reasonable expectation that the 95% CI of the mean difference in carbon stocks does not include zero (typically 5 or more years but up to a maximum of 10 years since the project start date or most recent recalibration i.e., the model assessment period). In this case, the model should be used to predict *the change* in carbon stock(s) during the model assessment period rather than to predict *absolute* carbon stocks. Model parameters, both coefficients and inputs, must be the same as those used to estimate removals and against which credits have been claimed. The prediction of the mean change in soil carbon stock(s) must be compared against mean of observed changes at each of the permanent sampling stations.

One of three outcomes will result.

Outcome 1) Two of the following are true:

i) The mean model-predicted *change* in carbon stock(s) lies within the 90% CI of the observed mean *change* in carbon stock for each stratum and the 90% CI for the model overlaps with the 90% CI for observed *changes* AND/OR
ii)the linear mixed model analysis shows that the mean predicted changes are not different from observed changes ($P > 0.10$) after stratum effects have been included in the statistical model AND/OR
iii) MBIAS for the *change in carbon stocks* is -10 to 10%.

In this case, the model predictions on which prior claimed net removals and credits were based matches the observed changes. No modification of the model(s) for future calculations of net removals and verified emission reductions is/are required.

Outcome 2) Two of the following are true:

i) The mean model-predicted *change* in carbon stock(s) *is less than* the lower 90% CI for the observed *changes* AND/OR
ii)the linear mixed model shows a difference between predicted and observed changes with $P < 0.10$, with mean predicted *changes* less than observed changes AND/OR
iii) MBIAS for the *change in carbon stock(s)* is less than -10%.

In this case the model has proved to be **conservative**. Project proponents may continue with the model, with the same parameters and coefficients, used during the model assessment period in doing future carbon calculations and verifications. Alternatively, the proponents *may choose* to undergo a re-calibration of the model, following the requirements of VMD0053, to more closely match observed changes in carbon stocks.

Outcome 3) Two of the following are true:

i) The mean model-predicted change in carbon stock(s) is greater than the upper 90% CI of the observed changes in carbon stock(s) AND/OR
ii)The linear mixed model shows a difference between predicted and observed *changes* with $P < 0.10$, with mean predicted changes *greater* than observed changes AND/OR
iii) MBIAS for the *change* in carbon stock*(s)* is *greater* than 10%.

In this case, the model has proved to be **optimistic.** To continue the project, proponents *must* undergo a re-calibration of the model, following the requirements of VMD0053, to more closely match observed changes in carbon stocks and must estimate the overage in previously claimed credits based on the observed mean changes in carbon stocks. This overage must be compensated from the non-permanence buffer and repaid by credits from future verifications before future verified credits are sold.

Finally, if the model is re-calibrated, its uncertainty must also be re-assessed using Monte Carlo or other analytical methods (8.4.2) in order to adjust any uncertainty discount in future verifications.

APPENDIX 4: TRANSITIONING FROM *VM0026, V1.0* AND *VM0032, V1.0*

The revised methodology VM0032 v 2.0 "Sustainable Native Grasslands Management through Adjustment of Fire and Grazing" is intended to be in effect for all Verra projects currently using VM0026 v 1.0 and VM0032 v 1.0. The key changes that project proponents need to make to complete this transition are discussed below

VM0026

1. *Applicability Conditions*
   A. Projects are no longer required to demonstrate they are in a designated "degraded" area. In fact VM0032 v 2.0 allows for recent improvements in baseline grazing or fire management, so long as they are accounted for by an increasing linear trend in baseline carbon stocks. Since current projects under VM0026 and VM0032 v 1.0 have already demonstrated degradation in the project zone, this change is likely of little consequence.
   B. VM0026 required independent estimates of methane and nitrous oxide emissions from both dung and soil. VM0032 v 2.0 does not allow nitrogen fertilizers to be added to project area soils, which renders N_2O emissions de-minimis. Requirements for limits to the proportion of project area (< 2%) with heavy dung deposition (more than 50% of soil covered by dung) render potential CH_4 and N_2O emissions from dung *de minimis*. If the area with heavy dung deposition is likely to be greater than 2%, GHG emissions from dung may not be de-minimis, and projects would be required to transition to the latest version of VM0042 .
   C. For both VM0026 and VM0032 projects, there is no requirement for "control" of livestock. Any displacement of livestock outside the project area is accounted for as leakage.
2. *Methane Emissions*
   Methane emissions in VM0026 are based on reported literature values for the country, region or project zone, or Tier I estimates based on IPCC defaults. VM0032 v 2.0 requires estimates of livestock numbers through censuses or surveys and then using a published allometric equation to convert animal body size into daily methane emissions per animal (see section 8.1.3.1 of this methodology). This requirement implies quantification of the following parameters N_c, $W_{c,y}$, $DMEF(W_{c,y})$ for at least four out of 10 years prior to the year of methodology transition.
3. *Models, Assessment, and Re-Assessment*
   Under VM0026, proponents were required to use a peer-reviewed published model that had been shown to predict SOC measurements or changes in the same climate zone as the project area. Under VM0032 v 2.0, proponents will now be required to either follow the requirements of the latest version of Verra module VMD0053 "Model Calibration, Validation, and Uncertainty Guidance for the Methodology for Improved Agricultural Land Management" or to follow the procedures outlined in section 8.1.3. and Appendix 3 of this methodology. Effectively this requires models that would have at minimum satisfied the former climate zone requirement of VM0026 but are now required to demonstrate their direct

applicability to the project area. This applicability can be achieved through model calibration and assessed by comparison with SOC measurements from the project zone or from appropriate peer-reviewed or government data sources (see VMD0053 for details).

A. Model selection

Following VMD0053 guidelines for model selection, at least one model version must be published in a peer-reviewed journal. However, many models have subsequent formal versions that can be selected by proponents provided these versions are publicly available and their parameters, functions and coefficient values are documented. Thus, proponents transitioning from VM0026 have the option of adopting a new model version.

Model Calibration

For an appropriately selected model, proponents may adjust the values of coefficients or inputs of the model to align with conditions in the project area. For this, proponents need two datasets of either 1) carbon stocks at the project start or 2) previous measurements of changes in carbon stocks – one for calibration and one for "validation" or what is called "assessment" in this methodology. Calibration datasets can be separate from project area data or a randomly drawn subset of project area data. They must not overlap with data used to validate or assess the model. For more details, see procedures in VMD0053

B. Assessment

Assessment of model accuracy and bias was not required in VM0026, but is required in VM0032 v 2.0. Assessment requires comparison of carbon stocks or carbon stock changes at each of a large number of sampling units (mean stock or changes in instances, mean stock or change in fields or pastures, or stock or change at individual representative sampling points. These data must be separate from data used in calibration. VM0032 v 2.0 requires a statistical association between these values to be evaluated and meet certain criteria for the model to be judged sufficiently accurate and unbiased for use in determining claimed removals (see Appendix 3).

In transitioning from VM0032 v 1.0, project models will have already met the criteria for approval under v 2.0, since the standards for comparing predicted and observed initial SOC of $R^2 > 0.80$, slope not significantly different from 1, intercept not significantly different from zero, and bias < 20% meet the criteria outlined in 8.1.3.3 and Appendix 3.

C. Re-*Assessment*

An important feature of projects that use models to claim credits is that they re-assess model accuracy and re-calibrate calculated removals periodically during the project lifetime. Proponents transitioning from VM0026 will now be required to perform a second model "validation" or assessment, this time in it's ability to predict **changes** in carbon stocks that are measured in the project area. For this methodology (VM0032 v 2.0) these changes will have been measured by a second round of sampling at a large number of representative sample points across the project area. Appendix 3 provides the requirements for whether prior project issuances based on the model are 1) underestimates (where deviations can be conservatively excluded), 2) matches (requiring no change to the project model), or 3) overestimates (requiring compensation of future issuances to the buffer and model re-calibration

4. *Model Uncertainty*

In VM0026, model uncertainty was based on the range of model results using the upper and lower 95% confidence limits of certain inputs to the model. Under VM0032 v 2.0, model uncertainty is evaluated with Monte Carlo simulation as prescribed by the IPCC Second Assessment. Data available at validation should be the standard errors of the coefficients (documented with model version) and input data for the model and the results of at least 100 runs of the model, drawing randomly from coefficient or input parameter distributions implied by the standard errors.

5. *Fire and Aboveground Woody Biomass*

VM0026 and VM0032 v 1.0 both allow conversion of shrublands to grasslands in order to increase SOC, but grazing management projects are likely to lead to accumulation of aboveground herbaceous biomass and thus fire fuel and increasing frequency of fires. Consequently, VM0032 v 2.0 requires proponents to monitor changes in aboveground woody biomass in stratum *m* and sample point *j* in year *y,* $AWB_{m,j,y}$ to account for changes in aboveground woody carbon due to fires associated with project activity.

In addition, VM0032 v 2.0 requires monitoring of biomass of at least three fuel classes – herbaceous, fine woody, and coarse woody plants – in order to assess potential increases or decreases (in the case of a fire management project scenario) in the emissions of CH_4 and N_2O Determination of emissions or carbon stock changes from biomass burning requires assessment of burned area through use of MODIS Burned Area Product MCD64A1 https://modis.gsfc.nasa.gov/data/dataprod/mod45.php or FIRMs databases (https://firms.modaps.eosdis.nasa.gov/) to determine the location and area of fires. In addition, proponents will need to measure or obtain from the literature biomass combustion factors and emission factors for determining emissions from biomass burning

For the baseline, these new parameters that must be available at validation include

$BM_{b,m}$ = baseline pre-fire biomass (kg/ha) of fuel class *b* in stratum *m* at point *j*

MBA_m = mean area burned (ha) in stratum *m* over the 10 years prior to project start.

$BMAF_{b,m}$ = biomass of fuel class *b* after fire in stratum *m* (kg/ha)

$CF_{b,m}$ = combustion factor for fuel class *b* in stratum *z* (mean proportion of biomass burned) (this is calculated from the three above parameters

$EF_{N2O,b,m}$ = emission factor for nitrous oxide for fuel class *b* (g N_2O / kg biomass burned) in stratum *m*

$EF_{CH4,b,m}$ = emission factor for methane for fuel class *b* (g N_2O / kg biomass burned) in stratum *m*

Again, baseline parameters are monitored over the 10 years prior to baseline reassessment..

In the project scenario, proponents are required to continue monitoring the burned area and biomass parameters each year

$PBA_{m,y}$	=	area burned (ha) in burn stratum *m* during monitoring year *y*
$PBMAF_{b,m,y}$	=	project biomass of fuel class *b* in stratum *m* after fire in monitoring year *y* (kg/ha)
$PBM_{b,m,y}$	=	project biomass of fuel class *b* in stratum m before fire in monitoring year *y* (kg/ha)

APPENDIX 5: GUIDANCE ON POTENTIAL EMERGING TECHNOLOGIES TO MEASURE SOC CONTENT

Project proponents 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.[23]

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 project proponents 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 11 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.[24] Hence, although each individual measurement may be less accurate, many more measurements can 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 laboratory, 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 11.

[23] The listed technologies may be updated in future versions of VM0032 and VM0042. The use of remote sensing-based techniques for estimating SOC content is currently not allowed.

[24] 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), Article 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, and other factors
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% of the sample data is used for calibration/training and 30% for validation/testing. Other methods for data-splitting include k-fold cross-validation and bootstrapping.
7) Demonstration that calibration and statistical validation data are representative of the actual project area in terms of SOC content, clay type, clay content, Munsell soil color,[25] and application of organic amendments, where relevant.[26] 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 root mean square error (RMSE), R^2, ratio of performance to interquartile range (RPIQ), bias, and Lin's concordance correlation coefficient (CCC), or other suitable parameters
9) Description of the approach used to generate posterior predictive distributions (PPDs) or intervals 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% 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

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

[26] SOC content from quantification 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 11: Method-specific criteria to evaluate use of emerging technologies based on proximal sensing to measure SOC content

Method	Criteria and Considerations to Ensure Robustness and Reliability
Inelastic neutron scattering[27] (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 evaporation and atomization in the plasma. • Before analysis, soil material must be pressed to form a pellet with a flat surface. • 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 must be delay time and laser repetition rate. • 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"[28] may be applied, which explore the plasma physicochemical properties, use of analyte emission lines/transition energies with different sensitivities, 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.

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

[28] 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[29] 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), Article 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

[29] 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)

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Milori, D. M. P. B., Segnini, A., da Silva, W. T. L., Posadas, A., Mares, V., Quiroz, R., & Martin-Neto, L. (2011). *Emerging techniques for soil carbon measurements*. CCAFS Working Paper 2. CCAFS. Available at: https://hdl.handle.net/10568/10279

Nicolodelli, G., Marangoni, B. S., Cabral, J. S., Villas-Boas, P. R., Senesi, G. S., Dos Santos, C. H., Romano, R. A., Segnini, A., Lucas, Y., Montes, C. R., & Milori, D. M. B. P. (2014). Quantification of total carbon in soil using laser-induced breakdown spectroscopy: A method to correct interference lines. *Applied Optics*, *53*(10), 2170–2176. https://doi.org/10.1364/AO.53.002170

Segnini, A., Pereira Xavier, A. A., Otaviani-Junior, P. L., Ferreira, E. C., Watanabe, A. M., Sperança, M. A., Nicolodelli, G., Villas-Boas, P. R., Anchão Oliveira, P. P., & Milori, D. M. B. P. (2014). Physical and chemical matrix effects in soil carbon quantification using laser-induced breakdown spectroscopy. *American Journal of Analytical Chemistry*, *5*(11), 722–729. https://doi.org/10.4236/ajac.2014.511080

Senesi, G. S., & Senesi, N. (2016). Laser-induced breakdown spectroscopy (LIBS) to measure quantitatively soil carbon with emphasis on soil organic carbon. A review. *Analytica Chimica Acta*, *938*, 7–17. https://doi.org/10.1016/j.aca.2016.07.039

Villas-Boas, P. R., Franco, M. A., Martin-Neto, L., Gollany, H. T., & Milori, D. M. B. P. (2020). Applications of laser-induced breakdown spectroscopy for soil analysis, part I: Review of fundamentals and chemical and physical properties. *European Journal of Soil Science*, *71*(5), 789–804. https://doi.org/10.1111/ejss.12888

Villas-Boas, P. R., Franco, M. A., Martin-Neto, L., Gollany, H. T., & Milori, D. M. B. P. (2020). Applications of laser-induced breakdown spectroscopy for soil characterization, part II: Review of elemental analysis and soil classification. *European Journal of Soil Science*, *71*(5), 805–818. https://doi.org/10.1111/ejss.12889

MIR and (Vis-)NIR, including DR and DRIFT spectroscopy

Barthès, B. G., & Chotte, J. L. (2021). Infrared spectroscopy approaches support soil organic carbon estimations to evaluate land degradation. *Land Degradation & Development*, *32*(1), 310–322. https://doi.org/10.1002/ldr.3718

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APPENDIX 6: DEFINITIONS OF SOIL SLOPE CLASSES FOR USE IN SETTING BASELINE CONTROL SITES

Table 12. Soil slope classes

Slope Class	Slope (Gradient) Class Limits	
	Lower (%)	Upper (%)
Low Slope	≥0	<9
Moderate Slope	≥9	<30
Steep Slope	≥30	

Adapted from USDA Natural Resource Conservation Service (NRCS) (2017). Chapter 2.—Landscapes, geomorphology, and site description Table 2-3. In: *Soil survey manual handbook no. 18* 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 12.
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).