Methodology for GHG and Co-Benefits in Grazing Systems

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1. METHODOLOGY OVERVIEW

1.1. SCOPE

This *Methodology Protocol* is intended to provide a holistic assessment of multiple ecological state indicators for grasslands under the practice of prescribed grazing. It can be used by *Project Proponents* and other stakeholders to obtain estimates of Soil Organic Carbon (SOC) stocks within a project area, and measure additional ecological co-benefits such as animal welfare, ecosystem health, and soil health.

The general guidance is intended to assist *Project Proponents* in applying a measurement-based soil organic carbon approach focused on maximizing accuracy of SOC stock estimation, while minimizing sampling efforts and costs. Soil sampling coupled with Remote sensing data or more traditional spatial interpolation methods will be used to calculate SOC stocks. Soil samples will also be used to assess soil health while remote sensing data and peer reviewed literature will provide an assessment for ecosystem health.

The main ecological health indicator assessed in this methodology is:

- CARBON SEQUESTRATION
    - Soil Organic Carbon (SOC) stocks and CO_2 equivalents (CO_2e)

Additional Co-Benefits assessed are:

- SOIL HEALTH
    - pH
    - Macronutrients
        - Nitrogen, Phosphorus, Potassium
    - Cation Exchange Capacity - CEC
    - Minor nutrients:
        - Calcium, Magnesium, Potassium, Sodium, Aluminum
- ANIMAL WELFARE
    - Measured using standards aligned with the project area locale
- ECOSYSTEM HEALTH
    - Ecosystem Vigor
        - Normalized Difference Vegetation Index (NDVI)
    - Ecosystem Organization
        - Woody vegetation landscape metrics
        - Protected perimeter of wetlands and watercourses
    - Ecosystem Resilience
        - Bare Soil Estimation (BSI)

1.2. A MEASUREMENT-BASED SOIL ORGANIC CARBON METHODOLOGY

Several steps are required to estimate the long term changes in soil organic carbon stocks within a project area:

1. Develop a soil sampling plan for the project area according to Section 3.1.
2. Sample collection and preparation
3. Laboratory analysis of soil samples
4. Estimation of SOC stocks for the project area
5. Converting SOC stocks to CO_2 equivalent stocks
6. Calculating the change in CO_2e stocks between monitoring periods

A schema for the measurement-based approach to estimate changes in SOC stocks is presented in Figure 1. SOC stocks measured in the first sampling round (i.e. the Baseline), are compared to those calculated in subsequent sampling rounds to quantify changes in carbon stocks after project commencement. This methodology outlines two approaches for estimating carbon stocks. The first method is an innovative approach based on using remote sensing data to calibrate statistical models to estimate SOC stocks. This approach allows for a significant reduction in the number of soil samples that must be collected by the *Project Proponent* as compared to traditional sampling. The second method adopts a traditional extrapolation approach in which SOC stocks are calculated using soil samples extracted during an intensive sampling effort.

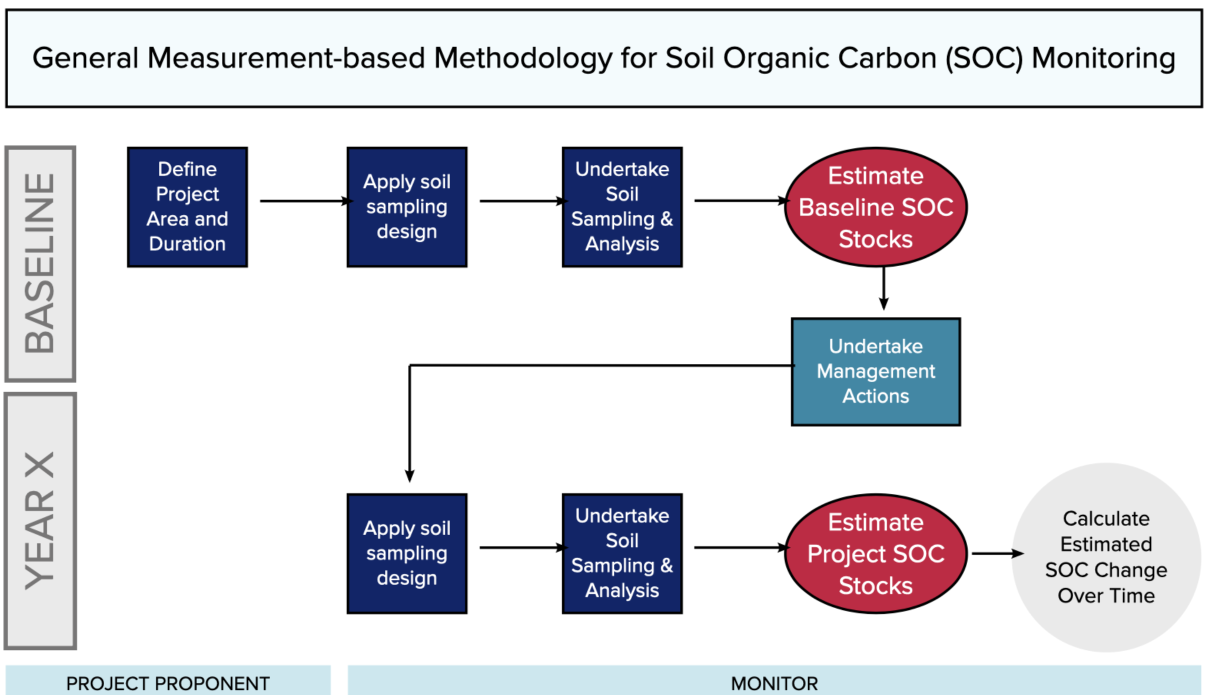

Figure 1: Main Steps for assessing changes in SOC stocks within a project area.

1.3. CO-BENEFITS

The co-benefits are intended to allow for a holistic assessment of the project area beyond carbon sequestration. The soil health, ecosystem health, and animal welfare metrics are chosen based on their widespread use as known, reliable indicators sensitive to the changes in ecological state.

1.3.1. SOIL HEALTH INDICATORS

Soil health indicators assess soil performance and functionality[1]. Chemical indicators such as pH, macronutrients, minor nutrients and Cation Exchange Capacity values can be used to assess changes in soil function and are sensitive to variations in management. Thus, chemical indicators will be ranked according to local benchmarks for the project region and project soils (see Section 4).

1.3.2. ECOSYSTEMS HEALTH

Ecosystem health is assessed holistically through the use of context-dependent indicators of ecosystem vigor, organization and resilience.

1.3.3. ANIMAL WELFARE

The American Veterinary Medical Association[2] defines Animal Welfare as the means by which "an animal is coping with the conditions in which it lives. An animal is in a good state of welfare if (as indicated by scientific evidence) it is healthy, comfortable, well-nourished, safe, able to express innate behavior, and if it is not suffering from unpleasant states such as pain, fear, and distress. Good animal welfare requires disease prevention and veterinary treatment, appropriate shelter, management, nutrition, humane handling, and humane slaughter." Animal welfare evaluations are often locale specific. Regional guidelines and variations should be taken into account during the evaluation.

2. PROJECT BOUNDARY

2.1. SPATIAL BOUNDARIES

The spatial boundary encompasses all land on which the *Project Proponent* will undertake the *Proposed Activity*. Spatial boundaries defining the project area should be provided by the *Project Proponent* with any parcels or stratification schemes defined. Acceptable data formats include polygon shapefiles, geopackages, KML/KMZ files and GeoJSONs.

2.1.1. MASKING FOR GRASSLANDS AREA

To ensure proper estimation of soil organic carbon stocks, any man-made objects such as roads or buildings, woody vegetation, bodies of water and other land types not included within the bounds of the *Proposed Activity* must be excluded. A mask representing grasslands under the practice of prescribed grazing must be provided. This mask can be created using GIS and remote sensing tools, land cover algorithms, visual inspection or any other method chosen by the *Monitor* or *Project Proponent*.

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[1] NRCS USDA Soil Health
[2] AVMA: Animal Welfare: What Is It?

2.2 TEMPORAL BOUNDARIES

The *Project Timeframe* is the period of time during which the *Project Proponent* will undertake the *Proposed Activity*. Current available data from scientific literature on sequestration rates from agricultural grasslands (e.g. Prescribed Grazing) is limited[3], but based on the available data and industry knowledge, it can take up to 10 years to build up enough carbon stock to warrant credit issuance. The monitoring period and frequency defining the temporal boundaries should adhere to the following guidelines:

- The minimum number of soil sampling rounds for a 10-year crediting period is five (5)
- Soil sampling rounds must be conducted on the first and last years of the project
- It is recommended that two (2) soil sample rounds occur consecutively during the first two years
- It is recommended that two (2) soil sample rounds occur consecutively during the last two years
- The minimum duration between monitoring periods is one (1) year
- The maximum time between soil sampling rounds is three (3) years

The example below outlines an acceptable soil sampling timeline during the 10-year crediting period.

Example: Years during which soil sampling occurred are shown in red. Two consecutive sampling rounds are set at the beginning of the crediting period: at the beginning (S1, 'baseline'), and at the end of first year (S2). The third sampling round (S3) is performed at the end of year 4, the fourth sampling round (S4) is performed at the end of year 7, and the last sampling round (S5) is set at the end of year 10.

Note: The schema described above can be modified if an extreme climatic event or disaster is declared for the area of the project.

3. CALCULATING THE CARBON SEQUESTRATION AND NET GHG REDUCTION

3.1. COLLECTION OF DATA

3.1.1. SAMPLE SIZE

The number of samples in the soil sampling plan is determined according to the approach selected for quantifying soil organic carbon. Traditional sampling methods (i.e intensive sampling) will require a much larger sample size than the remote sensing approach which uses the equation defined in Section 3.1.1.1. to stipulate a minimum number of samples needed to calibrate remote sensing data. If traditional sampling is used, please refer to one of the tools/resources listed in Section 3.1.1.3. to determine the appropriate level of samples required for the project area. The minimum number of samples required by either approach must be met to achieve a reliable and

[3] See for example NRCS data for Prescribed Grazing in Table 3 adapted from Swan et al [2015]

statistically valid level of rigor. Monitoring periods where the number of samples falls below the minimum could result in a deviation. In this case please contact the science@regen.network.

3.1.1.1. MINIMUM SAMPLE SIZE ESTIMATION FOR SATELLITE CALIBRATION

The soil sample size required **to calibrate satellite data** and estimate soil organic carbon stocks depends on the project size. The sample size should be determined according to Equations 1-3 listed below, which use the number of hectares of grassland area within the project area as the input metric. It is important to note the minimum number of samples is calculated using the grasslands area defined in Section 2.1.1, not the total property area. Figure 2 illustrates the relationship between grassland area and sample size per unit area.

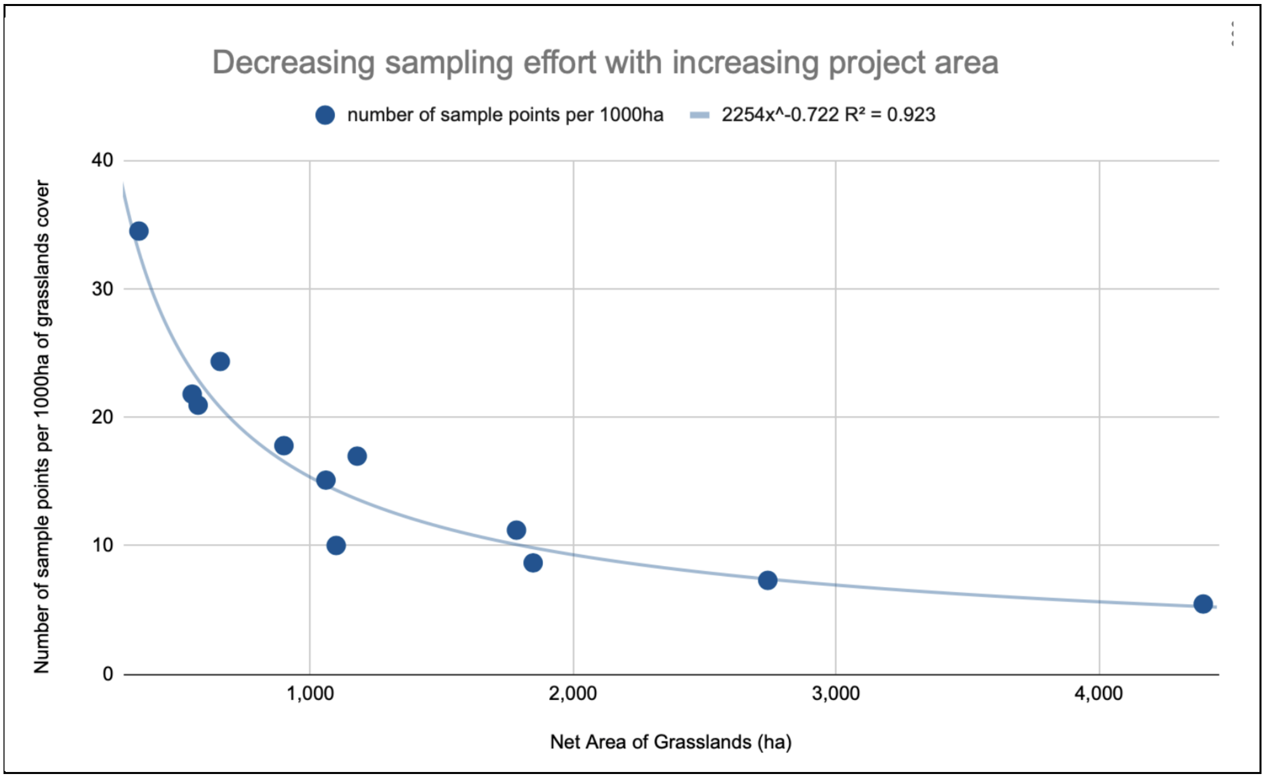

Figure 2. Relationship between the required number of sample points per 1000ha and the net project grasslands area.

The minimum number of sampling points for every 1,000 ha of grasslands (N_{1k}) needed to calibrate satellite data is estimated using Equation 1.

$$N_{1k} = 2254 * GrassArea^{(-0.72)} \qquad \text{(Eq. 1)}$$

where the net grassland area (GrassArea) of the project is in hectares.

The number of sampling points for the satellite calibration (N_{cal}) within the project area is then estimated as:

$$N_{cal} = (N_{1k} * GrassArea) / 1,000 \qquad \text{(Eq. 2)}$$

The total number of soil sampling points (N_{total}) for the project area must then be increased by 30% to account for any additional data needed to validate model performance when calculating soil organic carbon stocks:

$$N_{total}=N_{cal} + (0.3 * N_{cal}) \quad \text{(Eq. 3)}$$

It is highly recommended that three (3) soil subsamples cores are extracted at each sampling location and analyzed separately, in order to improve the total accuracy of the results and be able to discard outliers. Therefore, ***the total number of samples*** *to be analyzed at a certified lab would be equal to [*$\boldsymbol{N_{total}}$ ***x 3****]. However, the absolute minimum number of samples required is* N_{total}*. If the project does not meet these minimum requirements you must contact* science@regen.network.

3.1.1.2. ANCILLARY SOIL SAMPLE DATA

Ancillary data from other farms can be used to increase the sample size for satellite calibration if the number of samples falls below the required minimum. Any ancillary data used must meet the following requirements:

I. The sample dates for the project area and the sample dates for the farm providing the ancillary data must fall within one month of each other.
II. The project area and the farm providing the ancillary data must be within the same climatic region according to the Köppen Climate Classification System[4].
III. The project area and the farm providing the ancillary data must have been under the same management practices for at least 3 years.
IV. The project area and the farm providing the ancillary data must have similar soils and vegetation cover.
V. The sample extraction methods and sample analysis methods at the ancillary farm must match the protocols used for the primary farm

3.1.1.3. SAMPLE SIZE ESTIMATION FOR TRADITIONAL SAMPLING

In contrast to the remote sensing approach which uses correlations between satellite imagery and ground truth data to estimate soil carbon at unsampled locations, the success of the traditional sampling approach to measure soil organic carbon revolves heavily around intensive sampling. Reliable results can only be achieved by collecting enough samples to account for the project size and spatial variability of the soil. Topographic variation, hydrology, vegetation cover, and soil composition, such as percent clay, are just a few variables which could affect the spatial variability. Large project areas are also more likely to have a high variability of soil properties, so establishing a sampling plan to cover the entire range of these variables is crucial to providing an accurate assessment.

[4] Beck et al. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution

The traditional sampling plan may be determined by the *Monitor* or *Project Proponent*. The chosen approach for defining the sample size must be accompanied with a justification supported by peer reviewed literature or local guidelines detailing the sampling plan and the sample size calculations. The peer-reviewed resources below are examples of acceptable resources for developing a soil sampling plan.

A. Sampling protocols published in the peer-reviewed literature (e.g. de Gruijter *et al*[5, 6] ; Viscarra Rossel et al., 2016b[7])
B. Generating spatially and statistically representative maps of environmental variables to test the efficiency of alternative sampling protocols (Cunningham et. al, 2017[8])
C. Soil carbon stock in the tropical rangelands of Australia: Effects of soil type and grazing pressure, and determination of sampling requirement (Pringle et. al, 2011[9])
D. A geostatistical method to account for the number of aliquots in composite samples for normal and lognormal random variables (Orton et. al, 2015[10])
E. CFI Equal area stratification soil sampling design guidelines[11]
F. CDM Guidelines[12]
G. FAO guidelines 2019[13]

Note: these recommendations were adopted from The Supplement for the CFI Methodology 2018[14].

<u>*Design considerations*</u>: *It is good practice to employ oversampling at the design stage, not only to compensate for any high variance or outliers, but also to prevent a situation at the analysis stage where the required reliability was not achieved and additional soil sampling efforts would be required. The need for additional soil sampling would be expensive, time-consuming, and inconvenient*[15].

3.1.2. STRATIFICATION

In statistics, stratified sampling is a technique used to partition the population into subgroups, or strata, based on similar characteristics. Stratified sampling can help reduce the number of samples needed to measure soil health by segregating the landscape into subregions which share similar

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[5] De Gruijter et al. 2016. Farm-scale soil carbon auditing.
[6] de Gruijter et al. 2019. Using model predictions of soil carbon in farm-scale auditing - A software Tool.
[7] Viscarra Rossel, et al. 2010. Using data mining to model and interpret soil diffuse reflectance spectra.
[8] Cunningham et al. 2017. Generating spatially and statistically representative maps of environmental variables to test the efficiency of alternative sampling protocols.
[9] Pringle et al. 2011. Soil carbon stock in the tropical rangelands of Australia: Effects of soil type and grazing pressure, and determination of sampling requirement.
[10] Orton et al. 2015. A geostatistical method to account for the number of aliquots in composite samples for normal and lognormal random variables.
[11] Carbon Farming Initiative: Soil Sampling Design- Methods and Guidelines. 2014.
[12] Sampling and surveys for CDM project activities and programmes of activities (Version 3.0)
[13] FAO. 2019. Measuring and modeling soil carbon stocks and stock changes in livestock production systems: Guidelines for assessment (Version 1)
[14] The Supplement- To the Carbon Credits (Carbon Farming Initiative—Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018
[15] This is in accordance to Annex 4 Standard for Sampling and Surveys for CDM Project Activities and Programme of Activities

biophysical characteristics. Less samples are needed because the samples collected are representative of soil characteristics across the entire strata.

When to stratify?
Stratification should be applied if:

A. The spatial boundaries defined by the *Project Proponent* do not include pre-defined parcels or strata.
B. The spatial boundaries provided include a large number of parcels and there is a need to identify the most representative parcels to target.
C. The parcels provided by the *Project Proponent* are large and/or do not reflect the variability of soils, moisture, vegetation cover, hydrologic conditions, management history or other variables that might be affecting SOC in the topsoil. In this case, a stratification redefining parcels is recommended.

How to stratify?
Variables highly correlated to soil organic carbon can be used as proxies to divide the project area into strata encompassing the full range of SOC levels (low, medium and high). This approach will help establish a sampling plan which covers the full range of percent SOC values, thus providing more accurate stock estimates. Some variables found to be good proxies to spatial variability of SOC at the field scale include:

- Topographic: elevation, slope, aspect, erosion, terrain ruggedness Index (TRI) and the multi-resolution valley, bottom flatness index (MrVBF)
- Land Use / Land cover (LULC): Vegetation cover, above ground biomass, land management history
- Satellite Imagery: Multispectral satellite bands (e.g. Sentinel-2, Landsat TM), NDVI , BSI, NDWI, Tasseled Cap
- Hydrologic: topographic wetness index (TWI), catchment area and stream power index (SPI)
- Pedologic: soil types, clay content
- Other: pH

The project area can be restratified each soil sampling round as improved quality of information becomes available, however it is recommended sample locations remain consistent between monitoring rounds. If the stratification is used, any parcels defined in Section 2.1 should be replaced by or modified to match the stratified zones such that parcels fall within *only one* of the stratified zones. Any parcel which falls into two or more stratified zones should be broken down and redrawn such that new parcels are located within a single stratified zone.

The monitoring report must specify the methods and variables used to define strata and include a one-to-many relationship listing which parcels belong in each stratified zone. If parcels defined by the *Project Proponent* were re-drawn, the spatial boundary file created in Section 2.1 should be updated. A geospatial file defining stratified zones used for each monitoring round must be provided with each report.

Useful Resources:

- cLHS - Conditioned Latin Hypercube Sampling[16] [17]
- QuickCarbon Stratifi[18]
- Equal-range stratification[19]
- k-means [20] [21]
- A thorough review of variations on these methodologies authored by Biswas and Zhang (2018)[22].

3.1.3. ASSIGNING SAMPLE LOCATIONS

- Soil sample locations must be determined prior to any soil sampling performed.
- If stratification was used, at least one sampling location must fall within each strata class to ensure underlying variations in soil organic carbon are represented. This is a requirement needed for later analysis.
- Geolocations for soil sampling units must be selected at random. GIS tools, such as the QGIS "random points inside polygons tool", can be useful for creating random sampling points.
- It is recommended that sample locations remain consistent between rounds, though if sample locations differ, it is crucial to record the GPS coordinates for the newly sampled locations
- There are various approaches to establishing sample locations using a traditional sampling framework. Please reference the resources provided above and select a sampling plan that is appropriate for the project location and variability. If traditional sampling is used, the approach used to determine the sampled locations within the project area must be provided and justified according to peer reviewed literature and/or local sampling protocols.

3.1.4. EXTRACTING SAMPLES

It is important that samples used for soil carbon quantification follow proper sample collection and preparation procedures. Improper collection or preparation of soil samples can result in substantial errors, which can render the results of expensive sampling rounds unusable and compromise the integrity of the results. Please refer to the Soil Sampling Guide for in depth recommendations for soil sampling instructructions.

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[16] White. 2019. cLHS - Conditioned Latin Hypercube Sampling
[17] Minasny and McBratney. 2006. A conditioned Latin hypercube method for sampling in the presence of ancillary information
[18] QuickCarbon Stratification Tool
[19] Hengl et al. 2003. Soil sampling strategies for spatial prediction by correlation with auxiliary maps
[20] Viscarra Rossel and Brus. 2018. The cost-efficiency and reliability of two methods for soil organic C accounting
[21] Brus et al. 1999. A sampling scheme for estimating the mean extractable phosphorus concentration of fields for environmental regulation
[22] Biswas and Zhang. 2018. Sampling Designs for Validating Digital Soil Maps: A Review

Regen Network recommends the following instructions to collect soil samples:

1) Prior to core extraction, clear the sample location of living plants, plant litter and surface rocks.
2) Recommended sampling depth of 15cm, unless otherwise specified by the lab or location specific recommendations (justification must be provided if sample depth differs from 15cm)
3) The sampling depth must be the same at all sample locations in all given carbon estimation areas. The only exception to this is where the nominated sampling depth cannot be reached due to bedrock or impenetrable layers. In this situation, the actual sampling depth must be recorded.
4) The sampling depth must be consistent between all sampling rounds (i.e if samples are collected at 15cm for the baseline, samples must be collected at 15cm for following monitoring rounds)
5) A GPS device with a minimum precision of 4 meters must be used to record the sampling point in the field
6) If subsamples are taken more than 4 meters apart, the sample location for each subsample should be recorded
7) Samples must be taken at least 10 meters away from any tree, structure, or body of water
8) Please refer to Section 2.1 in the Soil Sampling Guide for the recommended soil sample collection tools.
9) If the soil profile is altered (incorporating substances external to the profile, or vertically altering the profile – eg. tilling, clay delving, water ponding) the sampling depth must be at least 10 cm below the depth of profile alteration.
10) Report the day, month and year for each sample collected within the given sampling round.
11) It is a requirement that all sampling rounds occur at least 6 months after the application of non-synthetic fertilizer.

Each laboratory has specific soil sample collection instructions. Clients may choose a laboratory that is certified in their local area, or a part of a land-grant institution. Please refer to Table 1 in the Soil Sampling Resource Guide for a list of laboratory specific instructions, laboratory accreditation requirements, approved laboratories, soil tests offered, and estimated costs.

Report must include:

- Tools and methods used to estimate number of samples
- Sample stratification method and stratification map
- Tool used to extract soil cores
    - If core sampler used, include tool diameter in mm
- GPS coordinate for each sample location and sub-samples (if applicable)
- GPS device used to record sample locations

Additionally, the *Project Proponent* must provide the raw lab reports to the *Monitor*.

3.2. SAMPLE ANALYSIS

3.2.1. WHAT TO MEASURE?

To quantify SOC stocks, percent soil organic carbon and bulk density must be measured for each soil sample. Additional metrics used to assess soil health can vary between project location, soil type, and vegetation present.

The metrics assessed for each soil sample must include:

1) Percent soil organic carbon
2) Bulk density
3) pH
4) Macronutrients
    a) Phosphorus
    b) Potassium
    c) Nitrogen (at least one of the following)
        i) Total Nitrogen
        ii) Nitrate Nitrogen
        iii) Ammonium Nitrogen
5) CEC (cation exchange capacity)
6) Minor nutrients: at least three of the following:
    a) Calcium
    b) Magnesium
    c) Potassium
    d) Sodium
    e) Aluminum

Additional local parameters that are relevant to the project location and management activity can be included in the soil health assessment. Benchmarks for these indicators must be clearly indicated. More details on this process can be found in Section 4.

3.2.1.1 BULK DENSITY

Bulk density quantification may require the collection of a separate set of soil samples depending on the laboratory used. If bulk density measurements are not provided by the laboratory, it can be calculated using one of the following methods.

1. If laboratory analysis provides soil dry weight and volume, use the total soil volume dried in the laboratory protocols to calculate bulk density according to Equation 4.

   $$Soil\ Bulk\ Density\ (g/cm^3) = \frac{Dry\ Soil\ Weight}{Total\ Soil\ Volume}$$
   (Eq. 4.)

2. If only the sample core dry mass is provided by the laboratory analysis, then the volume of the sample will be calculated based on the number of cores (in the case of a composite

sample), the diameter of the coring device used, and the sampled depth (Equation 5). This volume can be used in the Soil Bulk Density equation above (Equation 4) to calculate bulk density. Check that units are appropriately converted to cm to ensure accurate bulk density measurements.

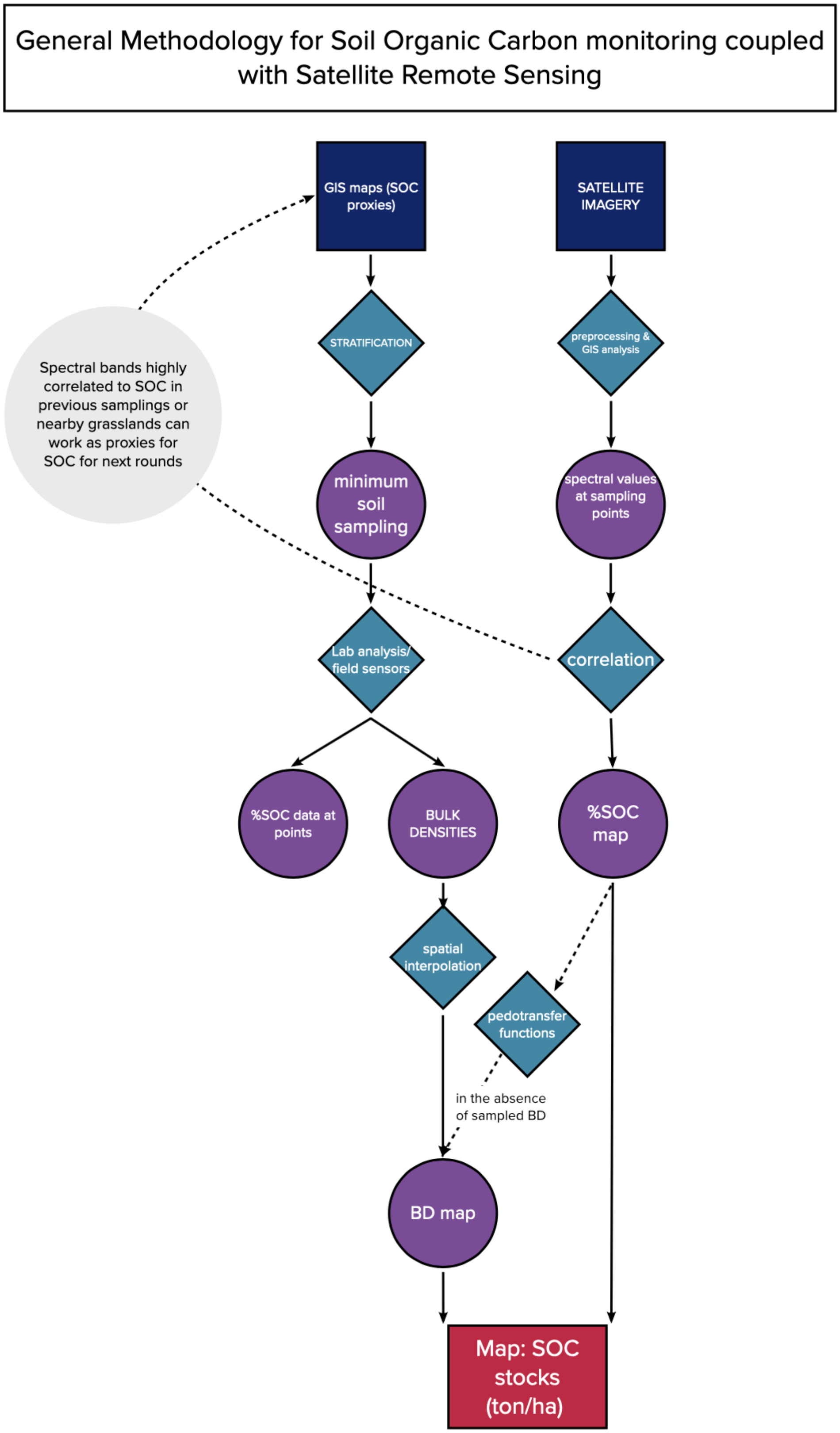
$$Total\ Soil\ Volume(cm^3)\ =\ number\ of\ cores\ *\ \pi\ *\ (Core\ Radius)^2 * Sample\ Depth$$
(Eq. 5.)

3. Bulk density can be collected, processed, and analyzed on location/in-field using the Ring Method outlined in Section 3 of the Soil Sampling Guide. This approach uses Equation 5 to calculate volume by using the radius of the ring rather than the radius of the coring device. Samples can be dried in a microwave to assess dry soil weight.

3.3. SOC STOCKS CALCULATIONS

Sections 3.3.1 and 3.3.2 outline two options for creating raster maps of percent soil organic carbon.
Section 3.3.3 and 3.3.4 provide for the steps to convert from soil organic carbon percentages to stocks and maps.

3.3.1. CALCULATING PERCENT SOIL ORGANIC CARBON: REMOTE SENSING APPROACH



3.3.1.1. EXTRACTING SPECTRAL VALUES AT SAMPLING POINTS

Satellite imagery and other remote sensing data can be paired with percent soil organic carbon values from collected soil samples to train statistical models and estimate soil organic carbon stocks. The GPS coordinates recorded at soil sample locations tie the two datasets together. Satellite imagery used for the remote sensing approach must have a spatial resolution of 20 meters or higher. Ancillary data, such as digital elevation models (DEMs), pedologic maps, and derived indices may also be used for analysis. Ancillary data does not have to meet the 20-meter spatial resolution requirement, however all data used during analysis must be resampled to match the spatial resolution of satellite imagery. Tables 1 and 2 provide examples of data which could be used for analysis.

Table 1. High resolution Sentinel-2 Bands and their corresponding wavelengths

Band	Resolution	Central Wavelength	Description
B2	10 m	490 nm	Blue
B3	10 m	560 nm	Green
B4	10 m	665 nm	Red
B5	20 m	705 nm	Red Edge 1
B6	20 m	740 nm	Red Edge 2
B7	20 m	783 nm	Red Edge 3
B8	10 m	842 nm	Near Infrared (NIR)
B8A	20 m	865 nm	Red Edge 4
B11	20 m	1375 nm	Short Wave Infrared 1 (SWIR 1)
B12	20 m	1610 nm	Short Wave Infrared 2 (SWIR 2)

Table 2. Remote sensing indices, topographic variables and soil data

Name	Description	Data Used
Normalized Difference Vegetation Index (NDVI)	NDVI is a measure of vegetation health	Near Infrared-Band 08 Red-B04 Equation: $\frac{NIR-Red}{NIR+Red}$
Normalized Difference Moisture Index (NDMI)	NDMI is a measure of vegetation water content	Near Infrared-Band 08 Short Wave Infrared-Band 11 Equation: $\frac{NIR-SWIR}{NIR+SWIR}$

Bare Soil Index (BSI)	BSI identifies bare ground cover within a landscape	Equation: $\frac{(Red+SWIR)-(Blue+NIR)}{(Red+SWIR)+(Blue+NIR)}$
Elevation	Elevation is a measure of the distance above sea level	Elevation
Slope	Slope represents the rate of elevation change from a digital elevation model	Elevation
Aspect	Aspect measures the slope direction	Elevation
Topographic Wetness Index (TWI)	TWI is a measure of topographic control on hydrological processes	Elevation
Percent Silt	A measure of the composition of silt in the soil from 5-15cm and from 15-30cm	NA
Percent Clay	A measure of the composition of clay in the soil from 5-15cm and from 15-30cm	NA

The workflow below outlines the method to calculate SOC stocks using Sentinel-2 imagery and ancillary data, however other high resolution imagery, such as PlanetScope, WorldView, or GeoEye, can be used. All images and ancillary data included in the analysis should be specified, and any preprocessing steps must be well researched, checked, and documented by the *Monitor* to assure the highest quality results.

1. Sentinel-2 imagery with a sensing date +/- 4 months around the sampling date should be downloaded as or preprocessed to Level-2A data products providing Bottom of Atmosphere (BOA) reflectance values. All images should be visually inspected by the *Monitor* to ensure there are no atmospheric irregularities or clouds covering the study area. Although clouds can be removed using cloud masking tools such as FMask, it is highly recommended cloud free images be used as cloudy images often affect results even if clouds don't directly cover the study area. The European Space Agency Sen2Cor correction tool can be used to atmospherically correct images and convert Level-1C data products to the Level-2A format. The *Monitor* must document any preprocessing tasks performed on Sentinel-2 tiles used for analysis.
2. If multiple Sentinel-2 images are available within the +/- 4 month period, images can be downloaded and averaged to smooth the data and reduce the effect outlying spectral values could have on analysis. All images included in the average must fit the criteria listed in (1). Images must be preprocessed *before* the average is performed.
3. Ancillary data such as the variables listed in Table 2 must be resampled to the same resolution as the satellite imagery. This data does not have to fall within the +/- 4 month sensing period as long as no significant change in the measured variable has occurred.

4. The QGIS[23] Point Sampling tool (or analogous tool) should be used to extract remote sensing data at each sampling location. This data should be exported and paired with soil organic carbon values to create a training dataset used for statistical analysis.

3.3.1.2. CORRELATION BETWEEN PERCENT SOC AND REMOTE SENSING DATA

5. Regression models should be fit to the dataset created in (4) to detect correlations between percent soil organic carbon and remote sensing data. The approaches below outline regression analyses which can be used to predict percent SOC. The *Monitor* may select any approach, but must provide a detailed report of the method used and any metrics used to evaluate accuracy and uncertainty.
    a) Simple Regression: Single linear regression and power regression models can be fit to each of the Sentinel-2 image bands included in analysis. Once models have been generated for all bands, model accuracy should be evaluated using a train-test split, R^2 value, root mean squared error (RMSE), and other standard accuracy metrics. The normalized RMSE (nRMSE) can be used to quantify model uncertainty. Once all models have been scored, the most accurate model should be selected to predict percent SOC for the project area. Design considerations:
        - Simple regression models can only be fit to satellite imagery; ancillary data or derived indices may not be used.
        - If a model scores below what would be considered statistically significant outliers may be removed to improve accuracy. Outlier removal should be performed using standard statistical techniques such as external studentized residuals, z-scores, or box plots. Removing too many outliers may result in overfitting and can compromise the size and reliability of the dataset, so any outlier removal must be justified by the *Monitor*.
        - The maximum value should be set to the maximum SOC % value from the samples from the Project Area. This is a conservative measure that prevents overestimations beyond the range of input values that were used to generate the model.
    b) Machine Learning: In contrast to simple regression models which can only detect correlations with a single variable, machine learning models can estimate soil carbon using a larger set of variables. These types of models can be useful in more complex study areas by discovering patterns that more basic regression models might overlook. It is important to note, however, that machine learning models are stochastic. Meaning the random nature of how they are trained will produce slightly different SOC stock predictions every time they are run. With this in mind it is recommended any machine learning model used be run multiple times. Final results and reported accuracy metrics should be an average of multiple iterations. This approach reduces the potential for extremes to occur and smooths the data to provide more reliable and conservative estimates. Accuray for machine learning models can be evaluated using a train-test split and the mean absolute percentage error (MAPE).

[23] Point Sampling Tool Plugin for QGis

6. Use the model selected in (5) its corresponding Sentinel-2 bands and/or ancillary data to estimate percent SOC at unsampled locations. The raster output from this step is a SOC map for the entire project area.

See Supplement 3 for information and resources on automation tools which can be used to help carry out steps 1-6.

3.3.2. CALCULATING PERCENT SOIL ORGANIC CARBON USING A TRADITIONAL SAMPLING APPROACH

Spatial interpolation methods such as kriging, Inverse Distance Weighting (IDW), or splining can be used to estimate percent soil organic carbon at unsampled locations if the traditional sampling approach in Section 3.1.1.3 was used to collect soil samples. The spatial interpolation method used to estimate percent soil organic carbon should be specified by the *Monitor*. Uncertainty from the resultant percent SOC raster must be assessed using a train-test split or any other approach supported by peer reviewed literature.

3.3.3. MAPPING SOC STOCKS

Converting percent soil organic carbon to soil organic carbon stocks requires bulk density and soil depth measurements to incorporate soil volume into stock calculations. Soil depth is a constant value which corresponds to the depth of the soil samples taken in Section 3.1.4. Bulk density can be estimated using one of the following approaches:

1. **Spatial interpolation:** Spatial interpolation algorithms such as kriging, Inverse Distance Weighting (IDW), or splining can be used to estimate bulk density values at unsampled locations. The resulting bulk density estimates should be scored and assessed using methods such as cross validation and other prediction error statistics. The spatial interpolation method used should be specified by the *Monitor*.
2. **Pedotransfer functions:** Pedotransfer functions (PTF) relating percent soil organic carbon to bulk density may be used as a spatial extrapolation method to calculate bulk density for the project area. The pedotransfer function used should be supported by peer reviewed literature and assessed by comparing PTF estimates with bulk density values collected during sampling. The R^2 value and the normalized standard error of the estimate (nSSE) can be used as metrics of accuracy and uncertainty.

Soil organic carbon stocks are then calculated through map algebra by applying Equation 6 to the percent soil organic carbon and bulk density rasters, using soil depth as a constant. The resulting raster represents the total amount of soil organic carbon stocks in each pixel.

$$\textbf{SOC stock(ton/ha)} = \textbf{SOC\%} \times \textbf{BD (g/cm3)} \times \textbf{Soil Depth (cm)} \qquad \text{(Eq.6)}$$

3.3.4. CALCULATING FINAL SOC STOCKS

To ensure only grasslands are included in the final soil organic carbon stock estimate, the grasslands mask created in Section 2.1.1 should be used to estimate stocks. The QGIS zonal statistics tool (or equivalent tool) can be used to sum all pixels contained within the grasslands.

The resulting number is the **final soil organic carbon stock estimate** for the monitoring round. Please be sure to correct the spatial resolution of pixels to match units of tonnes per hectare before calculating the sum.

3.4. CONVERTING SOC STOCKS TO CO_2 EQUIVALENTS

Converting soil organic carbon stocks to CO_2 equivalent stocks can be done by multiplying the SOC stocks (in metric tons) by a conversion factor of 3.67:

$$CO_2\text{eq. (metric ton)} = \text{SOC (metric ton)} * 3.67 \qquad \text{(Eq. 7)}$$

3.5. CALCULATING THE GREENHOUSE GAS EMISSIONS

3.5.1. EMISSIONS FROM LIVESTOCK

Greenhouse Gas (GHG) emissions from livestock must be recorded each year to accurately calculate creditable carbon change. Calculating livestock emissions must be performed in accordance with IPCC or relevant national/state/regional scale factors. Equation 8[24] shows how livestock emissions should be calculated using the number of animals present, the number of days the animals were located in the project area, and a default emission factor for the corresponding group of livestock. Annual emissions from each year must be added to calculate total GHG emissions before each crediting period. The livestock type, region, and the source of the emission factors must be cited in the report.

$$E_{liv} = Q \times D \times EF_{liv}/1{,}000 \qquad \text{(Eq. 8)}$$

where:

E_{liv} is the total emissions from livestock for a particular year for the project area, in metric tons of CO_2e.

Q is the number of animals within the project area in that year, in livestock head.

D is the number of days in the reporting period that the livestock was within the project area.

EF_{liv} is the default emission factor for the livestock, according to its type, as set out for the particular region; in kilograms of CO_2e per livestock head per day.[25]

There are many ways livestock head can be reported as per the *Project Proponent*. For example:

1. If total livestock head is reported for a monitoring year, use total livestock head for **Q** and the number of days in the project area for ***D.***
2. If livestock head is provided in terms of opening and closing head for a given monitoring year, take the average between the two for **Q** and set the number of days in project area **D,** to 365.
3. If livestock head is recorded for each quarter of a monitoring year, take the average of the four quarters for **Q**, and set the number of days in project area **D**, to 365.

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[24] Carbon Credits (Carbon Farming Initiative—Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018

[25] An example of emission factors for Australia can be found in the Supplement to the Carbon Credits (Carbon Farming Initiative)

3.5.2. EMISSIONS FROM FERTILIZER

If fertilizers are used within the Project Area, Greenhouse Gas (GHG) emissions from fertilizer ($\mathbf{E}_{\mathbf{Fertilizer}}$) inputs must be recorded each year to accurately calculate creditable carbon change. Calculating fertilizer emissions must be performed in accordance with IPCC or relevant national/state/regional scale factors.

The *Project Proponent* should provide fertilizer specific information as it relates to the project area including a) the type of fertilizer used and b) the mean annual fertilizer input during the monitoring period (often reported in kg). Use conversion factors (often with units of tCO_2e/kg fertilizer) aligned with specific fertilizer types, to convert kg of fertilizer to annual emissions in tCO_2e.

The fertilizer type, mean annual fertilizer input, conversion factor and final emission quantification must be cited in the report.

3.6. CALCULATING THE CREDITABLE CARBON CHANGE

3.6.1. BASELINE DEFINITION

The baseline SOC stocks or CO_2e are defined here as the total carbon stocks calculated for the project's *Initial Monitoring Date*, or date of the first sampling round. The methodology adopts a project-based, static baseline which is calculated as the total SOC stocks, in metric tons, from the *Initial Monitoring Date.* All sampling rounds after the *Initial Monitoring Date* will be compared to the baseline to calculate creditable carbon change.

3.6.2. CHANGES IN CO_2e BETWEEN REPORTING PERIODS

The change in SOC stocks between reporting periods is estimated as the difference between the total SOC stocks from the second monitoring period, minus total SOC stocks from the previous period (Equation 9).

$$\textbf{SOC stock change} = \textbf{tSOC}_{(t+1)} - \textbf{tSOC}_{t} \qquad \text{(Eq. 9)}$$

The same applies for estimating the change in the total SOC converted into CO2 equivalents between two sampling periods (Equation 10).

$$\mathbf{CO_2e\ change} = \mathbf{CO_2e}_{(t+1)} - \mathbf{CO2e}_{t} \qquad \text{(Eq. 10)}$$

3.6.3. NET CO_2e REDUCTION

The net CO_2e reduction in the project area for a given reporting period is calculated as the difference between the changes in SOC, expressed as metric tons of CO_2e, minus the total GHG emissions, also in CO_2e units:

$$\mathbf{NET\ CO_2e\ REDUCTION} = \mathbf{CO_2e\ change} - \mathbf{E}_{\mathbf{liv}} - \mathbf{E}_{\mathbf{Fertilizer}} \qquad \text{(Eq. 11)}$$

3.6.4. UNCERTAINTY AND DEDUCTIONS

Under this methodology framework, the total uncertainty for the project is a sum of the uncertainties calculated throughout the methodology during a given monitoring period. Sources of uncertainties for creditable carbon stock calculations include percent soil organic carbon estimates, bulk density estimates, and any deviations from the original methodology which might have introduced additional errors.

Approaches to quantifying uncertainty for a given monitoring period depend on methods used to calculate monitoring variables. If linear regression models were used the standard error of the Estimate (SEE) or the normalized root mean square error (nRMSE) would provide reliable accuracy metrics, but the same is not true for when measuring uncertainty for spatial interpolation or machine learning models. With this in mind, uncertainty should be quantified using the best available science. The *Monitor* can assess uncertainty using methods supported by peer reviewed literature, or by consulting model experts who have either developed or worked directly with the model in an academic setting. Suggested methods for calculating uncertainty for percent soil organic carbon and bulk density can be found in Supplement S.2. Guidelines for Uncertainty Assessment.

If the uncertainty (U) for the reporting period is less than or equal to 20%, the *Monitor* may use the net CO_2 reduction value generated in Section 3.6.3 without making any deductions to account for uncertainty (ex. Uncertainty Deduction (UD) = 0). If uncertainty is greater than 20%, the *Project Proponent* must use the Uncertainty Deduction (UD) values in Table 3 to calculate the amount of uncertainty to deduct from the creditable carbon stocks. Uncertainty deduction values are based on the Gold Standard LUF activity requirements Version 1.2.1[26]. Examples for uncertainty deduction are shown below.

Table 3. Ranges of uncertainties and the corresponding discounts.

UNCERTAINTY (U)	Uncertainty Deduction (UD) (% of U)
U≤20%	-No Deduction-
20%<U≤30%	50% of U
30%<U≤40%	75% of U
40%<U≤50%	100% of U

[26] Gold Standard LUF activity requirements Version 1.2.1

Examples:

- U=10%--> UD=0%
- U=25%--> UD=25% * 0.5= 12.5 %
- U=35%--> UD=35% * 0.75= 26.25 %
- U=45%--> UD=45% *1= 45%

The maximum uncertainty allowed for any measurement in the project is 50%. The *Creditable Carbon Change* after Uncertainty Deduction is then estimated as:

CREDITABLE CARBON CHANGE =(NET CO_2e REDUCTION)×(1−UD) (Eq. 12)

4. CALCULATING THE SOIL HEALTH INDICATORS

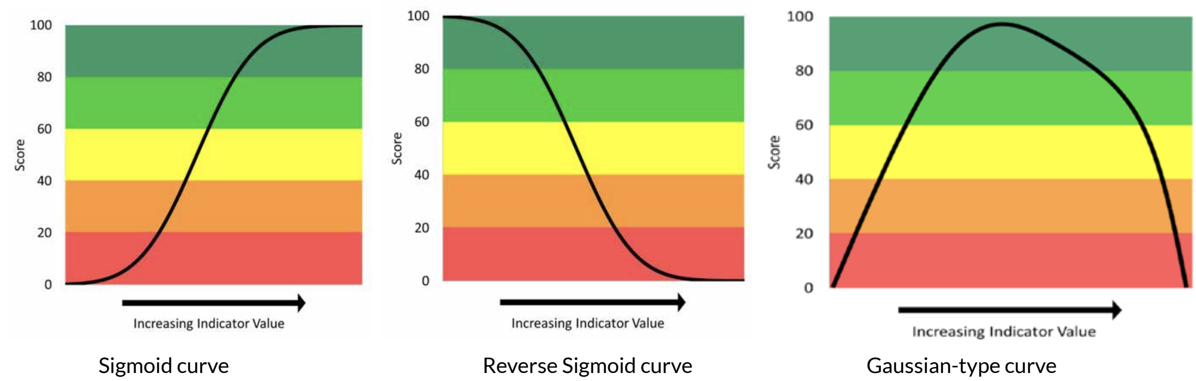
The main soil health indicators for Grasslands projects are pH, macronutrients (Nitrogen, Phosphorus, and Potassium), cation exchange capacity (CEC), and other minor nutrients such as Calcium and Magnesium.

In order to assess the soil health of a pasture, the desired levels (i.e. benchmarks) of the most relevant soil health indicators for the Project Area must be established during the baseline period. These levels will vary depending on soil types and ecoregion.
The soil indicators to be assessed will be chosen according to their relevance for assessing soil health in the Project Area, and must include at least the following:

- Soil pH
- Macronutrients: Phosphorous, Potassium and at least one Nitrogen parameter (i.e. Ammonia, Nitrate or Total Nitrogen).
- CEC (Cation Exchange capacity)
- Minor nutrients: at least three minor nutrients from the following list:
    - Calcium
    - Magnesium
    - Potassium
    - Sodium
    - Aluminum

The *Monitor* could use the scoring approach proposed by the Cornell University Framework[27] to evaluate each of the soil-health variables. Under this approach, and depending on the indicator, there are different cumulative normal distribution scoring curves that can apply. For example, the chemical indicator potassium is scored using a sigmoid function that relates better scores to higher levels of potassium. Phosphorus and pH, on the other hand, are both scored using an optimum, Gaussian-type curve.

[27] Manual -Comprehensive Assessment of Soil Health - Cornell Framework



Scoring functions should be regionally adapted by the *Monitor* according to thresholds based on literature or local standards. For each monitoring period, each indicator will be ranked per sample according to the local benchmarks. There are two options for assessment on a per sample basis. The first being the establishment of a distinction between samples falling into optimal vs non-optimal ranges (aligned with the binary scoring section below). Samples categorized as "optimal" are those which fall within the desired levels based on the project's ecoregion and soil type. The second option is a non-binary assessment, where samples can fall into a "poor", "moderate", or "optimal" range (see non-binary scoring section below).

To incorporate the distribution of rankings across the samples for each indicator, the following decision tree is used to determine the final ranking.

<u>Binary Scoring</u>

If the local benchmarks for the assessed indicator only provide for optimal and non-optimal values, the classification score for the final ranking should be calculated using Equation13.

$$Classification\ Score\ = \frac{\Sigma\ Soil\ Health\ Ranking}{Total\ Number\ of\ Samples} *\ 100 \qquad \text{(Eq. 13.)}$$

Where *soil health ranking* is:

- Non-optimal = 0.25
- Optimal = 1

Please use the *Classification Score* to determine the final ranking according to Table 4.

Table 4. Soil Health Ranking for a Binary Classification:

Classification score	Final Ranking
0-25%	NEEDS IMPROVEMENT
>25-50%	FAIR
>50-75%	GOOD
>75-100%	EXCELLENT

Non-Binary Scoring
If the local benchmarks for the assessed indicator provide clear indications of poor, moderate and optimal ranges, the final rankings should be calculated using Equation 13.

Where *Soil Health Ranking is:*

- Poor: 0.33
- Moderate: 0.67
- Optimal: 1

Please use the *Classification Score* to determine the final ranking according to Table 4.
See Supplement Section 1.1 for a soil health assessment example.

4.1. pH

The optimal range of values for pH must be determined by the *Project Monitor* using local metrics for the region and specific soil type(s) found within the project area. Healthy pH levels for soil health follow an optimum, Gaussian-type curve. To estimate the optimum range for pH, build the normal distribution curve according to the average pH values of soil samples collected in the ecoregion. The optimal pH levels and standard deviations must be backed by a trustworthy scientific source and included in the report.

4.2. MACRONUTRIENTS (NPK)

4.2.1. NITROGEN

Nitrogen metrics measure the productivity of nutrient cycling functions in the soil. The most common indicators used to quantify soil Nitrogen are *Nitrate-Nitrogen*, *Ammonia- Nitrogen* and *Total Nitrogen*. An increase in the indicators of Nitrate-Nitrogen and Total Nitrogen lead to increased soil health, therefore both of these indicators follow a cumulative distribution function. Nitrate-Nitrogen and Total Nitrogen follow a cumulative distribution function, meaning an increase in either variable indicates better soil health. Ammonia-Nitrogen is different and follows an optimum curve.

In order to estimate curves for each parameter, the average values and standard deviations from pastures in the region must be reported. Alternatively, local scientific studies showing threshold values for optimum, moderate and poor categorization can be used as a reference to build the scoring ranges.

4.2.2. PHOSPHORUS

The availability of soil phosphorus varies with the acidity of the soil. The more acidic the soil, the more phosphate 'fixed' by the soil and made unavailable to plants. As a result, critical values for soil phosphorus change with the soil type. A cumulative distribution function best fits the relationship between soil health and phosphorus and should be used as the scoring curve for this indicator.

4.2.3. POTASSIUM

Plants amass potassium from two soil sources: exchangeable potassium that is immediately available, and non-exchangeable potassium which becomes available at much slower rate. Clay soils have a higher nutrient holding capacity than sandy soils and thus can have higher levels of immediately available potassium. In light of this fact, soil test interpretation and benchmark categorization must be based on soil texture, as the critical value increases with increasing clay content.[28]

A cumulative distribution function best fits the relationship between soil health and potassium and should be used as the scoring curve for this indicator.

4.3. CEC (CATION EXCHANGE CAPACITY)

'Exchangeable cations' give a measure of overall soil fertility. The cations—**calcium (Ca), magnesium (Mg), potassium (K), sodium (Na) and aluminium (Al)**—are added together to produce the cation exchange capacity (CEC). The higher the CEC, the more fertile the soil[10]. As a result, the cumulative distribution function best describes the relationship between CEC and soil health. The curve and benchmark values for CEC are calibrated according to the mean and standard deviation of regional data. In the absence of local threshold values, missing information for setting benchmark values can be reconstructed using Cornell's approach[29].

4.4 MINOR NUTRIENTS

The following nutrients can be quantified and reported individually according to the scoring system.

- Calcium
- Magnesium
- Potassium
- Sodium
- Aluminum

Thresholds for these categories will be defined and justified according to the best knowledge for the project area (scientific papers, local reports).

[28] Brown Book. What are the optimum nutrient targets for pastures?

[29] Comprehensive Assessment of Soil Health - The Cornell Framework Manual

5. CALCULATING THE ECOSYSTEM HEALTH INDICATORS

The general framework used to evaluate ecosystems health[30] was originally proposed by Costanza (1992)[31] and later refined in 1999 by Costanza and Mageau[32]. According to Costanza, a healthy ecosystem has the ability to maintain its structure (organization) and function (vigor) over time in the face of external stress (resilience)[33]. This framework provides the foundational basis for methodologies which can assess ecosystem health dynamics and changes in grassland ecosystems.

5.1. ECOSYSTEM VIGOR

Ecosystem vigor is widely used as a primary factor for quantifying ecosystem health[34]. The vigor of a system is a measure of its activity, metabolism and/or primary productivity[35].

5.1.1. NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a good indicator of ecosystem vigor, and has been used in previous research for the assessment of the ecosystem health using remote sensing[36]. NDVI is calculated using visible (red) and near-infrared light reflected by vegetation (Equation 14). Healthy vegetation absorbs most of the visible light (red) while reflecting a large portion of the near-infrared light resulting in a high NDVI value. In contrast, unhealthy vegetation reflects the visible light (red), while absorbing more of the near-infrared light[37] and typically have lower NDVI values.

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad \text{(Eq. 14)}$$

To measure ecosystem vigor for grasslands in the project area, NDVI values for a project must be compared to the values in the surrounding region. The following steps are followed for scoring the vigor of the grasslands within a project area:

1. Create a 10km square or circular buffer around the project area using the extent of the spatial boundaries defined in Section 2.1.
2. Download and pre-process one or more satellite images following steps and specifications described in Section 3.3.2.2. Image sensing dates must be the same as or as close to dates of images used to calculate soil organic carbon stocks. Any pre-processing methods used should be documented.

30 Xu and Guo. 2015. Some Insights on Grassland Health Assessment Based on Remote Sensing
31 Costanza R. 1992. Towards an operational definition of health. In: Ecosystem health: new goals for environmental management
32 Costanza R. 1999. What is a Healthy Ecosystem?
33 Costanza R. 2012. Ecosystem health and ecological engineering
34 Xu and Guo. 2015. Some Insights on Grassland Health Assessment Based on Remote Sensing
35 Costanza R. 1999. What is a Healthy Ecosystem?
36 Xu and Guo. 2015. Some Insights on Grassland Health Assessment Based on Remote Sensing
37 Normalized Difference Vegetation Index (NDVI). NASA Earth Observatory

3. Calculate NDVI for the 10km buffered zone surrounding the project area using the pre-processed Sentinel-2 images generated in (2).
4. Create a grasslands mask using methods from Section 3.3.2.5 to remove any man-made objects, trees, bodies of water or other such land types from the NDVI image. Visually inspect the mask to ensure its accuracy.
5. Calculate the average NDVI value within the project area using the QGIS zonal statistics (or equivalent) tool. Next, calculate the average NDVI values within the masked 10km buffer zone created in (1).
6. Compare the NDVI averages between the project area and the buffer zone and generate a score based on the scoring chart below.

Scoring:
EXCELLENT: Project average NDVI is >25% higher than the NDVI of the 10km buffer area.
GOOD: Project average NDVI is 10-25% higher than the NDVI of the 10km buffer area.
FAIR: Project average NDVI is within an interval of +/- 10% the average NDVI of the 10km buffer areaN.
NEEDS IMPROVEMENT: Project average NDVI is below 10% lower than the average NDVI of the 10km buffer.

The report must include the NDVI results from buffer and project areas, and a link to the buffer vector file and the NDVI raster used.

5.2. ECOSYSTEM ORGANIZATION

Costanza (2012)[38] defined the organization of a system as the number and diversity of interactions between system components. Species diversity and the number of pathways and patterns of material and information exchange between the components both affect measures of organization.

The amount of primary vegetation is a key indicator of the organizational status of an ecosystem[39]. In the case of natural grasslands, the typical proportion of grasses to woody species varies across ecoregions. A well managed grassland ecosystem should have a ratio of woody vegetation cover to grassland similar to ratios found in natural, "wild" grasslands in the surrounding ecoregion. Also, the presence and ecological state of other components of the landscape affecting the diversity of interactions must be accounted for, like wetlands, water courses, forests or any natural reservoirs.

5.2.1 WOODY VEGETATION LANDSCAPE METRICS

Woody vegetation is a key component of most natural grassland ecosystems. Some landscape metrics like the proportion of woody vegetation cover, the patch sizes, the distances between patches, and / or the shape of the patches of woody vegetation can be used as indicators for the level of organization in grasslands. The metrics that should be chosen for a particular project

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[38] Costanza R. 2012. Ecosystem health and ecological engineering.
[39] Li et al. 2013. Three-Dimensional Framework of Vigor, Organization, and Resilience (VOR) for Assessing Rangeland Health

heavily depend on the ecoregion of the project area and the minimum needs for key species or endangered species that inhabit that ecosystem.
Based on remote sensing data and GIS analysis, the chosen landscape metrics must be estimated at the same time interval, or season, for each year from a land cover classification. For the land cover classification, imagery with a spatial resolution of 20 meters or higher, such as Sentinel-2 (ESA), must be used. The satellite source, GIS software and classification procedure (e.g. supervised nearest neighbor, random forest machine learning algorithm) used for the estimation of woody vegetation cover must be specified in the report, and images must be pre-processed following the workflow described in Section 3.3.1.1. There are several tools that can be used in GIS to estimate landscape metrics. We recommend the use of the LecoS (Landscape Ecology Statistics) plugin in QGIS, which is based on Fragstats.

For each reporting period, a single measurement of each landscape metric is required. The benchmarks for the excellent-good-fair-needs improvement ranking of the woody vegetation landscape metrics must be set locally according to the natural ecosystems characteristics and the key or endangered species in the ecoregion. The choice of landscape metrics and thresholds for scoring must be based on pertinent information from scientific literature. The corresponding cites to the scientific literature must be provided in the report.

5.2.2. PROTECTION OF WETLANDS AND WATERCOURSES

In case there are water courses of any kind (rivers, streams, permanent or intermittent) and/or wetlands within the project area, the percent of the total water course perimeter protected from animal entry will be quantified.

Scoring:
EXCELLENT: 100% of the perimeter of watercourses and wetlands are protected from animal entry.
GOOD: The percentage of the perimeter of wetlands/ watercourses in the project area that is protected from animal entry is higher than 70%.
FAIR: The percentage of the perimeter of wetlands/ watercourses in the project area that is protected from animals varies between 50-70%.
NEEDS IMPROVEMENT: Less than 50% of the perimeter of wetlands/ watercourses in the project area is protected from animal entry.

5.3. ECOSYSTEM RESILIENCE

Resilience represents the ability for an ecosystem to maintain its structure and function in the presence of stress, and can be measured by the system's capacity to return its original state following perturbation[17].

5.3.1. BARE SOIL ESTIMATION

Bare soil (i.e. [1 - vegetation cover]) has been identified as a good indicator of ecosystems resilience[40] and grasslands health[41]. The Bare Soil Index (BSI) is a numerical indicator estimated from satellite imagery that combines blue, red, near infrared and short wave infrared spectral bands to capture soil variations. These spectral bands are used in a normalized manner. The short wave infrared and the red spectral bands are used to quantify the soil mineral composition, while the blue and the near infrared spectral bands are used to enhance the presence of vegetation. The formula to calculate the BSI using Sentinel-2 imagery is specified in Equation 15[42]:

$$\text{Sentinel 2 MSI: } BSI_{S2} = \frac{(Band_{11} + Band_{4}) - (Band_{8} + Band_{2})}{(Band_{11} + Band_{4}) + (Band_{8} + Band_{2}} \qquad \text{(Eq. 15)}$$

In order to have a relative estimation of the bare soil within the project area versus the surrounding areas, the following steps are carried out for scoring the ecosystem resilience:

1. Create a 10km square or circular buffer around the project area using the extent of the spatial boundaries defined in Section 2.1. Save the results to a shapefile, geopackage, GeoJSON, or other GIS vector file.
2. Download and preprocess satellite imagery that falls within +/- 1 month from the reported sampling period. Sentinel-2 (10 square meters) or higher resolution is required and must meet the requirements and pre-processing steps specified in Section 3.3.1.1.. Averaging several dates without clouds around the sampling period increases the accuracy of the results.
3. Create a grasslands mask using methods from Section 2.2.1 to remove any man-made objects, trees, bodies of water or other such land types from the buffered and project areas. Visually inspect the mask to ensure its accuracy.
4. Calculate the BSI for the project area and the buffered zone created in (2). The resulting BSI raster must be validated through visual inspection of imagery performed by the *Monitor* or ground truth data provided by the *Project Proponent* to find the range of BSI values that accurately reflect only bare soil areas on the ground.
5. Calculate the area covered by bare soil within the Project Area only, using zonal statistics and the grasslands mask created in (3).
6. Calculate the area covered by bare soil within the 10km-buffer area only, using zonal statistics and the grasslands mask created in (3).
7. Estimate the areas covered by bare soil in both the project area and the buffer area.
8. Compare the percent bare soil cover between the project area and the buffer area and use the scoring chart below to generate a score for ecosystem resilience.

[40] Li et al. 2013. Three-Dimensional Framework of Vigor, Organization, and Resilience (VOR) for Assessing Rangeland Health

[41] Ludwig et al. 2000. Monitoring Australian Rangeland Sites Using Landscape Function Indicators and Ground- and Remote-Based Techniques

[42] Spectral Indices with Multispectral Satellite Data

Scoring:
EXCELLENT: Project Area has a percentage cover of bare soil that is notably lower than the percent bare soil cover in the surrounding zone. The difference is higher than 50%.
GOOD: Project Area has a percentage cover of bare soil that is lower to the percent cover in the surrounding zone. The difference is smaller than 50% and higher than 20%.
FAIR: Project Area has a percentage cover of bare soil that is +/- 20% of the percent bare soil cover in the surrounding zone.
NEEDS IMPROVEMENT: Project Area has a percentage cover of bare soil that is higher than 20% with respect to the surrounding zone.

The BSI results from the buffer and project areas must be included in the report.

6. CALCULATING THE ANIMAL WELFARE RANKING

The Animal Welfare ranks within 4 possible categories (Needs Improvement- Fair- Good- Excellent) depending on the percentage of accomplished items from local recommendations. Refer to Supplement Section 1.2 for an example of Australian requirements. The report should include statements regarding compliance with the requirements chosen for the project.

Scoring:

NEEDS IMPROVEMENT: <40% requirements are met.

FAIR: Between 40% and 70% requirements are met.

GOOD: >70% requirements are met.

EXCELLENT: 100% requirements met

7. OVERALL SCORING

1. SOC: Total tCO2e from section 3.6.4.
2. CO-BENEFITS:

The following scoring system shall be followed, using Table 5 as a template for the calculation of the final scores for the main Co-Benefits.

7.1. QUALITATIVE EQUIVALENCIES FOR FINAL SCORES

This framework outlines the equivalent rankings for the Final Score for the Soil Health metrics, Ecosystem Health metrics, and Animal Welfare metrics.

- Final Score ≤ 0.40 = *NEEDS IMPROVEMENT*
- 0.40 < Final Score ≤ 0.60 = *FAIR*
- 0.60 < Final Score ≤ 0.80 = *GOOD*
- Final Score > 0.80 = *EXCELLENT*

7.2. SOIL HEALTH AND ECOSYSTEM HEALTH SCORES

Weights for partial Ecosystem Health and Soil Health scores:

- Needs Improvement point = 0.25
- Fair point = 0.50
- Good point = 0.75
- Excellent Point = 1

FINAL SCORE = Sum of the partial Weighted Points / Total number of points

Calculation Example of the final score for Ecosystem Health

If the partial resulting scores for each indicator of Ecosystem health were:

- Organization = GOOD = 0.75
- Vigor = FAIR = 0.50
- Resilience = EXCELLENT = 1.00

Then the final average score for Ecosystem Health is estimated as :

Ecosystem Health = (0.75+0.5+1)/ 3 = *0.75 (GOOD)*

Weights for partial Animal Welfare scores:

See Section 6 above and Supplement 1.2 below for an example of animal welfare metrics.

- NEEDS IMPROVEMENT: <40% requirements are met.
- FAIR: Between 40% and 70% requirements are met.
- GOOD: >70% requirements are met.
- EXCELLENT: 100% requirements met

Table 5. Template for the calculation of the partial and total scores of the Co-Benefits..

<table>
<tr><th rowspan="2">MAIN INDICATOR</th><th rowspan="2">PARTIAL INDICATOR</th><th colspan="4">Rating (cross-check the corresponding rating)</th><th rowspan="2">FINAL SCORE</th></tr>
<tr><th>Needs Improvement</th><th>Fair</th><th>Good</th><th>Excellent</th></tr>
<tr><td rowspan="8">Soil Health</td><td>pH</td><td></td><td></td><td></td><td></td><td rowspan="8">Qualitative NI-F-G-E according to sum of weighted points</td></tr>
<tr><td>Nitrogen</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Phosphorus</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Potassium</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CEC</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Minor Nutrient 1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Minor Nutrient 2</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Minor Nutrient 3</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Scores for Soil Health</td><td></td><td></td><td></td><td></td><td>Write here Total Score and Qualitative Result</td></tr>
<tr><td>MAIN INDICATOR</td><td>PARTIAL INDICATOR</td><td>Needs Improvement</td><td>Fair</td><td>Good</td><td>Excellent</td><td></td></tr>
<tr><td rowspan="3">Ecosystem Health overall score</td><td>Vigor</td><td></td><td></td><td></td><td></td><td rowspan="3">Qualitative NI-F-G-E according to sum of weighted points</td></tr>
<tr><td>Organization</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Resilience</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Scores for Ecosystem Health</td><td></td><td></td><td></td><td></td><td>Write here Total Score and Qualitative Result</td></tr>
<tr><td colspan="2">Score for Animal Welfare</td><td></td><td></td><td></td><td></td><td>Write here the Qualitative Result</td></tr>
</table>

* NI=Needs Improvement; F=Fair; G=Good; E=Excellent

8. DATA REPORTING

8.1. REPORT

After each monitoring round, a report must be submitted to the Regen Registry including a description of the methods used for soil sampling, analysis of samples, as well as the equations and references used. The reported results for each section of this Methodology must be accompanied by all the information that supports them. In the case of GIS or remote sending data, it is required that the maps are included as images within the report for illustrative purposes. The original vector and raster files must be kept by the *Monitor*. Any documentation containing calculations and statistical analysis should also be saved.

8.2. DATA STORAGE

All data used during the analysis should be held by *Monitor* and/or *Project Proponent* for monitoring verification. This data includes:

- All raster and vector data used in geospatial analysis to generate results for any section of the methodology.
- A copy of all laboratory reports.
- All the relevant field data from the soil sample collection process (dates, tools, procedures, sample locations).
- Documentation outlining calculations and results of statistical analysis.

9. DATA VERIFICATION

The *Verifier* should verify the following items within each section:

9.1. SOIL ORGANIC CARBON DATA

- Data reported in the soil lab reports must match the data used during soil carbon. These data include:
  - Percent soil organic carbon
  - Bulk density
- Spectral values extracted from the satellite imagery and ancillary data match the data used during analysis.
  1. The *Verifier* should download the original imagery and ancillary data used and follow the pre-processing steps used by the *Monitor*
  2. Following the steps outlined in Section 3.3.1.1, spectral values should be extracted and compared to the data used to generate statistical models.
- Models used to estimate percent soil organic carbon should be re-created and compared to reported values.
- Final soil organic carbon stock estimates should be recreated and compared to reported values.

9.2. GHG EMISSIONS

- Using the data provided by the *Project Proponent* animal emissions should be recreated and compared to the reported values
- Using the data provided by the *Project Proponent* fertilizer Emissions should be recreated and compared to the reported values

9.3. SOIL HEALTH INDICATORS

- Data from the original soil lab reports must match the data used to assess soil health. These data include:
    - pH
    - Macronutrients
        - Phosphorus
        - Potassium
        - Nitrogen (at least one of the following)
            - Total Nitrogen
            - Nitrate Nitrogen
            - Ammonium Nitrogen
    - CEC (cation exchange capacity)
    - Minor nutrients: at least three of the following:
        - Calcium
        - Magnesium
        - Potassium
        - Sodium
        - Aluminum
- Reported soil health ranking should be assessed to ensure that they match reported rankings

9.4. ANIMAL WELFARE

- Review animal welfare rankings to ensure the proper number of requirements were met.

9.5. ECOSYSTEM HEALTH

- NDVI:
    - Assessment of the NDVI analysis used over the project area
    - Visual inspections on the ground or by remote sensing for the project area and surrounding area
- Woody Vegetation Landscape Metrics:
    - Assessment of the remote sensing protocols used to analyze presence of woody vegetation within the project area
    - Visual inspections on the ground or by remote sensing
- Bare Soil:
    - Assessment of the remote sensing protocols used to analyze bare soil within the project area

- Visual inspections on the ground or by remote sensing in both the project area and surrounding fields

SUPPLEMENTS

S.1. CO-BENEFIT EXAMPLES

S.1.1. SOIL HEALTH EXAMPLE ASSESSMENT

pH Example:

Methodology Description:

The standard method of measuring soil pH in [project area] is to use a 1:5 (soil:water) suspension method.

Benchmarks:

- According to [source], within [project area] "plant growth, and most soil processes, are favoured by a pH range between 5.5 and 8" . Within this range, an optimal range of pH is 6-7 .

Given these ranges, the soil pH ranking for pastures in X is:

-POOR: < 5.5 or > 8.0

-MODERATE: > 5.5 and <6.0 or >7.0 and 8.0<

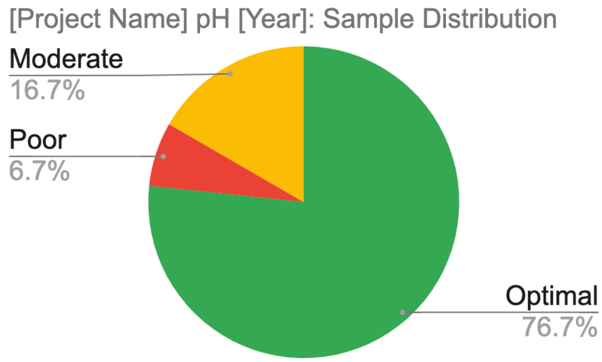
-OPTIMAL: 6.0 - 7.0

Results:

- Average pH values from [monitoring year] [project name] soil samples: [average of all samples]

- According to the ranking system the classification for [monitoring year] samples falls into the [Poor/Moderate/Optimal] range

The distribution of the pH rankings for the [project name] [monitoring year] data falls within the ranges illustrated below:



S.1.2. ANIMAL WELFARE EXAMPLE

An example of animal welfare metrics are outlined below according to Cattle Standards and Guidelines for Australia. The Animal Welfare metric ranks within 4 possible categories depending on the percent of accomplished items from the following list (more detailed information Australian Animal Welfare Standards). The calculation is only considered in relation to the total number of items that are applicable to the project.

1. Responsibilities: Are responsibilities fully addressed, clear responsibilities outlined in individual role descriptions and supported by appropriate company policies and training?

2. Access to feed and water: Do the animals on this land have reasonable access to adequate and appropriate feed and water?

3. Risk management: Are records of risk management kept via company policies and monthly manager reports? Are animals managed to minimise the impact of threats to their welfare including, extremes of weather, natural disasters, disease, injury and predation? Are there inspections of the animals at intervals, and at a level appropriate to the production system? Are there systems in place to ensure appropriate treatment for sick, injured or diseased animals at the first reasonable opportunity?

4. Facilities: Are facilities constructed and maintained to allow humane treatment of animals to ensure their welfare?

5. Animal handling: Are staff trained in handling and management practices that are appropriate (such as low stress stock handling) to minimise the risk to the welfare of the animals? See details in Section 5 of Australian Standards linked above.

6. Castration / dehorning: Are the practices of castration, dehorning and spaying only done when necessary and in a manner that minimises the risk to the welfare of the animal, particularly pain and distress? See details in Section 6 of Australian Standards linked above.

7. Breeding: Are breeding and management practices appropriate to minimise the risk to the welfare of the animals? See details in Section 7 of Australian Standards linked above.

8. Calf raising systems: Are calf-rearing systems appropriate to minimise the risk to their welfare? See details in Section 8 of Australian Standards linked above.
9. Dairy: Are dairy animals managed to minimise the risk to their welfare? Is a daily inspection taking place of lactating dairy cows? Are there systems in place to minimise the heat stress of animals? Is tail docking only carried out under veterinary advice to treat injury or disease? Do the animals kept on feed pads for extended periods have access to a well drained area for resting?
10. Feedlots: Are animals in feedlots managed in a way that minimises the risk to animal welfare? See details in Section 10 of Australian Standards linked above.
11. Slaughtering: Where it is necessary to kill animals, is it done promptly, safely and humanely? See details in Section 11 of Australian Standards linked above.

S.2. GUIDELINES FOR UNCERTAINTY ASSESSMENT

Calculating uncertainty is complex and can vary depending on the methods used to calculate monitoring variables. The methods below outline a few approaches on how to quantify uncertainty according to this requirement, however other methods can be used if supported by peer reviewed literature, or by consulting model experts who have either developed or worked directly with the model in an academic setting.

S.2.1 ASSESSING UNCERTAINTY FOR STATISTICAL MODELS

The normalized standard error of the estimate (nSEE) can be used to measure the uncertainty associated with a statistical model. After the model is created, a residual comparison between the estimated values from the model and the observed values is carried out. A widely used statistical metric to assess the uncertainty from the model is the Standard Error of the Estimate (SEE), calculated as:

$$Standard\ Error\ of\ the\ Estimate\ =\ \sqrt{\frac{\Sigma\,(y - y')2}{n}}$$

The final uncertainty for the model can be estimated as:

$$nSSE\ =\ \frac{Standard\ Error\ of\ the\ Estimate}{Average\ SOC\ observation}$$

S.2.2. ASSESSING UNCERTAINTY USING CROSS VALIDATION

Cross validation is a technique which can be used to quantify accuracy and uncertainty for machine learning models and spatial interpolation methods. This technique involves splitting the dataset into two parts: a training set which will be used to build the model or interpolate values, and the test set used to test the model or interpolation method's accuracy. Uncertainty error is estimated by comparing predicted or interpolated values to those held out in the test set. These residuals can be used to quantify using the nSEE or mean accuracy percentage score (MAPE).

S.3. OPTION FOR AUTOMATION

Regen Network Development Inc. has built a series of work packages automating many of the workflows found within the methodology, greatly reducing the amount of time and work needed to complete a monitoring round. The two main workflows automated within this project are image processing (described in Section 3.3), and the calculation of CO_2 equivalent stocks and livestock emissions using the satellite-based calibration workflow (Section 3.3). The automated workflows, written in python, have been packaged into Docker containers and can run on any operating system. Functionalities of each automated workflow and instructions on how to install them can be found below:

S.3.1 SENTINEL-2 PREPROCESSING

The Sentinel-2 image preprocessing work package takes one or more ESA Sentinel-2 tiles and pre-processes them . Functionalities include:

- Atmospheric Correction to create BOA data products
- Band Subsetting
- Band Stacking
- Spectral Index Calculations: NDVI, NDWI, CRC, NDTI, VDI, BSI
- Cloud Masking
- Mosaicing
- Averaging (for one or more images with the same spatial extent and band count)
- Cropping to Area of Interest

For information on how to install and deploy Sentinel-2 image preprocessing automation work package, go to: https://github.com/regen-network/regen-s2-ard

S.3.2 CARBON STOCK ESTIMATION

The carbon stock estimation work package includes a variety of modules which can help calculate net CO_2 reduction and creditable carbon stock using the satellite-based calibration workflow (Section 3.3). Functionality of this work package includes:

- Extracting Spectral Values at Sampling Points
- Correlating Percent SOC to Satellite Imagery
- Using PTF to estimate bulk density
- Mapping SOC Stocks
- Calculating Final SOC Stocks using zonal statistics functions

For information on how to install and deploy the automated carbon stock estimation work package, go to: https://github.com/regen-network/open-science/grasslands