A roadmap for quantifying soil organic carbon change as an ecosystem service on grasslands and pastures

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Executive Summary:

The purpose of this Roadmap report is to assist developers in the choice of approaches that quantify soil organic carbon (SOC) as a measurable ecosystem good or service (EGS) from Canadian grazing and forage lands (herein called collectively ‘grasslands’). Although grasslands occupy nearly half of the land used for agriculture in Canada, the ability to confidently, reliably, and practically estimate changes in SOC under grazing and forage management practices is a gap in Canadian science. The ultimate objective (beyond the scope of this report) is to be able to build a system that will quantify the impact of grassland management on SOC to enable SOC to be established as a quantifiable and transactable EGS that will thereby encourage increased adoption of beneficial management practices (BMPs) to increase those EGS. The roadmap was developed with significant stakeholder consultation and feedback from two Technical Advisory Group (TAG) meetings and a broader stakeholder workshop including stakeholders from academia, government, private-sector, environmental market experts and industry groups.

SOC impacts soil quality, functionality, and health and is an important ESG resulting from interactions of ecological processes. Human actions affecting these processes can lead to loss or enhanced sequestration of carbon in the soil. Sequestering carbon in the soil is a natural pathway for removing carbon dioxide from the atmosphere, with added benefits to the broader ecosystem, and the goods and services derived from the ecosystem, at a low cost. Improved land management and agricultural practices can enhance the ability of soils to store carbon and mitigate climate change. It is estimated that conservation of ecosystems (such as grasslands, wetlands and forests) could provide more than one-third of the emissions reductions needed to stabilize global temperature increases below 2 C by 2030 under the Paris Accord (Griscom et al, 2017). Canada’s temperate grasslands are both vast in scale and comprise high soil carbon density (Janzen et al. 2002). SOC stocks in grassland systems are relatively stable compared to other ecosystems, but have the potential to increase with appropriate management making Canada’s grasslands a significant climate change mitigation opportunity.

SOC stocks can be measured directly, but it can take many years to detect a discernable change in SOC stocks due to significant variability in measurements, management, and weather. As an alternative, SOC stocks and their changes can be estimated with process models of SOC – but it is essential that those models are validated with high-quality empirical data.

The preferred approach selected for the roadmap is to utilize process models supported by measurements from a monitoring network of sites across Canada collecting high-quality data, called the Canadian Forage and Grassland Observation Network (CaFGON). The establishment of the new CaFGON is thus the critical and fundamental initial goal on the roadmap towards better, more practical quantification of SOC stocks and their changes.

The CaFGON will provide the foundational data of real-world grassland performance that enables project developers and producers to reliably quantify SOC stock change to capitalize on market opportunities from SOC stock increases, and for producers and policymakers to assess how forage and grassland management practices can impact SOC. The CaFGON will collect, manage, and share datasets of observed SOC change paired with information on management practices, soils, climates, forages, and

grasslands across Canada to validate and calibrate models. The CaFGON will leverage all the value possible from relevant past studies of grasslands but, importantly, it will also include new ongoing observations to provide the data to evaluate models for current grassland management and conditions. The steps to establish CaFGON are 1) capacity building through the development of an initial small-scale platform to include a data repository for existing datasets and compilation of existing and potential monitoring sites; 2) design and develop a strategy for a CaFGON; 3) secure funding for CaFGON; and 4) continuing improvement of CaFGON.

Additional funding is needed for all steps and the initiative will actively look for philanthropic funders, public and private grants, private sector investments, voluntary contributions, and financial incentives through ecosystem markets. The proposed roadmap provides a feasible and incremental route that effectively leverages resources to accomplish the SOC quantification needed to more effectively focus investment and action to achieve healthier, SOC-enriched agricultural land for Canada.

Glossary

Term	Description
Approach	A high-level method used to measure or quantify SOC stores or changes
BMPs	Best or Beneficial Management Practices – land or on-farm management or practice changes that are beneficial in terms of environmental impacts.
Ecosystem Good	A measurable or quantifiable product gleaned from an ecosystem
Ecosystem Service	A measurable or quantifiable service gleaned from an ecosystem
Forage land	Land used to grow forages for livestock. Typically, the stand will be regularly terminated and reseeded. This land also includes any annual crops between forage stands.
Grassland	Land where the dominant vegetative species are herbaceous grasses, forbs, and shrubs and for which the vegetation is permanent (not expected to be terminated and reseeded in future). Can be entirely native species, tame species, or a mixture.
Grazing and forage lands	This term encompasses all the grassland, forage land, and short-term pastureland as defined herein.
IMWEBs	Integrated Modelling for Watershed Evaluation of BMPs – cell-based IMWEBs watershed hydrologic model designed to quantify water quantity and quality impacts of BMPs at various scales.
Models	Models are developed to describe or predict SOC stocks or changes based on observed data (empirical models) or biogeochemical (process models).
Short-term tame pasture	Pasture of tame species where the vegetation stand will be regularly terminated and reseeded. Their land also includes any annual crops between pasture stands.
Standard	An overarching and recognized set of rules or guidelines for the quantification and accounting of SOC or carbon offsets.
Tool	A protocol, calculator, or model used to measure or quantify SOC stores or changes.
Uncertainty	A statistical measure of the amount of error in an estimate of a mean or average value. All model-based and direct measurements of SOC are estimates with an associated error.

Introduction

This report outlines a recommended roadmap towards efficient quantification of soil organic carbon (SOC) from beneficial management practices (BMPs) on Canadian forage and grasslands (hereafter collectively termed 'grasslands') as an ecosystem service. The fundamental objective of this work is to enable environmental markets for BMPs employed on Canada's grasslands.

There are two target streams of application: to make geographically comprehensive estimates of SOC change on grasslands for Canada and/or for regions within Canada, including individual provinces or sub-provincial areas; and, to make more detailed SOC change estimates for projects that include specific grassland parcels but which are not necessarily geographically comprehensive. Currently, there is no standard approach to quantifying grassland SOC change for environmental markets. Direct measurement approaches have no capability to project SOC change over time. Validated modeling approaches can project estimated SOC changes over time, but involve risks associated with the level of understanding of management impacts on SOC, and with the quality of underlying datasets used for validation and calibration. To address these challenges and gaps, this report is split into two sections:

Part 1 includes a review of SOC measurement and modelling methods, and the standards, policies and guidelines relevant to quantifying grassland SOC in the context of markets for ecosystem goods and services (EGS). Key criteria important to ensuring rigorous environmental incentives and markets are also examined. The review focuses on internationally agreed best practice where available, and accepted methods for the development of validated and science-based approaches.

Part 2 of the roadmap explores current and emerging quantification approaches for measurement of SOC *change*, and recommends a preferred cost-effective approach for quantifying SOC change in Canadian grasslands on a national scale. Integration of the recommended approach with other environmental goods and services quantification frameworks is also explored, and actionable steps towards building the recommended framework are suggested.

The roadmap was developed with significant stakeholder consultation and feedback from two Technical Advisory Group (TAG) meetings and a broader stakeholder workshop including stakeholders from academia, government, private-sector, environmental market experts and industry groups.

Grassland Soil Organic Carbon

Grasslands produce multiple EGS which could provide revenue streams for land managers. Since SOC interacts with many other aspects of the grassland ecosystem that could also be considered EGS (see Figure 1), an initial question a developer must ask when attempting to build such a tool is whether to split SOC as a stand-alone EGS, or combine it with other EGS' from grasslands.

A related question the developer will need to answer is whether they want to quantify SOC stocks as the primary ecosystem good, or SOC change as the primary ESG. The answers to these questions may be dictated by market conditions, standards, and/or policies, but are also subject to the ability of the tool or approach to quantify the primary ecosystem service or good.

The difference between total SOC stocks and SOC stock changes is intuitive, but merits a reminder

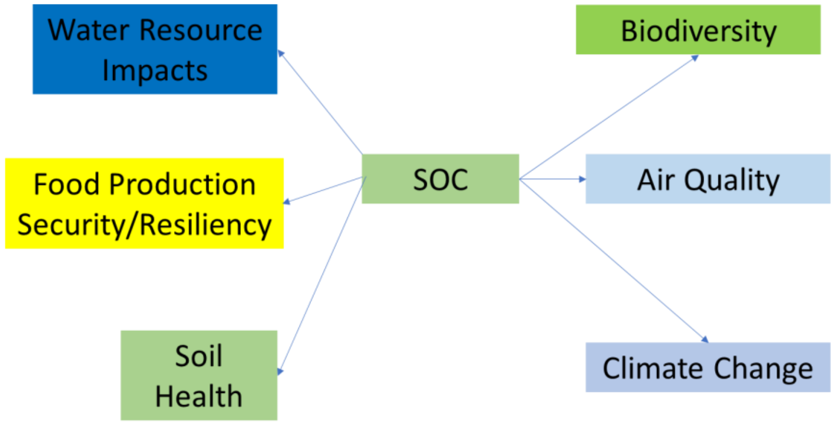

Figure 1: ESG related to SOC

ahead of the analysis that follows. Any credit or offset from grassland SOC will be related to a positive SOC stock change (from a change in management), or from the preservation of existing SOC stocks (prevention of SOC stock changes). Carbon stock changes are typically <1% or more of total carbon stocks per year. It is therefore much easier to measure to a given accuracy the total SOC stock, than it is to measure SOC stock changes. A quantification protocol to preserve existing SOC grassland stocks in Canada (not SOC changes) was recently published for use by the Climate Action Reserve, enabling this mechanism for EGS markets already[1].

1 The Canadian Grasslands Project Protocol, sponsored by Viresco Solutions and the Canadian Forage and Grasslands Association can be found here: https://www.climateactionreserve.org/how/protocols/canada-grassland/

The current approach to grassland carbon stocks in Canada's National Inventory Report (NIR), as defined by the IPCC, is to assume that if management has not changed over time, then grassland carbon stocks will remain constant. Due to a lack of data, Canada's NIR assumes grassland management has not significantly altered since 1990 and therefore does not account for any SOC stock changes on grasslands as a result of management or changing climate. This is recognized as a significant omission from Canada's NIR and, under the United Nations Framework Convention on Climate Change, Canada is now obligated to address this omission. Measurement of SOC change of permanent grasslands in France gave an average carbon sequestration rate of 0.57 tC/ha/yr – if this rate were also found in Canada, grassland SOC stock changes would more than fully offset GHG emissions from cattle.

Part One: Assessment of Existing Knowledge and Approaches

1. Quantification Approaches

The IPCC presents a 3-tiered classification of methodological approaches (see Table 1) to GHG emissions quantification, which can also be applied to the SOC quantification approaches discussed in this analysis. The tiers are differentiated according to the quantity of information required, the scale at which they are applied, and the degree of analytical complexity (IPCC, 2003, 2006, 2019; FAO-LEAP 2019). This classification is useful and commonly applied when comparing and contrasting different approaches to quantifying SOC stocks and changes.

Table 1: IPCC Tiers of Quantification, Distinction based on the approach

Approach	Method	Data Requirements	Aggregation Level/ Uncertainty	Example	Notes
Tier 1 Empirical Model	IPCC Tier 1 default equations and factors (FAO-LEAP Level 1 model)	Limited land use and management activity data, little soil delineation and vegetation types; no requirement for model calibration and validation; least data input/output complexity	Typically, large spatial units; National scale; annual resolution	IPCC GHG inventory guidelines	Suitable for rough overviews and where only limited data is available)
Tier 2 Model	Similar to Tier 1 approach with regionally specific empirical factors or with factors derived from validated process models	Intermediate spatial/temporal scale input data; land use and activity data stratified; intermediate requirement for model development and validation; modest data input/output complexity	Finer spatial and temporal resolution than Tier 1; can achieve reasonable uncertainty when good amount and quality of empirical data are used for model development.	Alberta conservation cropping protocol, (Comet-VR or CometFarm)	Suitable for roll-ups to regional to national scale; can be suitable for project-based, farm-specific accounting; empirical model is; useful for ISO 14064-2 compliant offset[2] since factors are usually the difference from a reference baseline.

2 - ISO 14064 Part 2: 2019 – Project Based Accounting Standard. A process-based standard with application at the Project Level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements between baseline and project emissions.

Tier 3 Process models	Soil-only process models (FAO-LEAP level 2); Soil C dynamics modeled but vegetation growth and removal is input not modeled	Spatially explicit fine-scale soils and land use data; annual C input data at fine-scale; daily/monthly climate data; intermediate requirement for model calibration and validation; intermediate data input/output complexity	Analysis at a spatial and temporal scale of model inputs but almost always at field/paddock scale and annual due to C input data; can achieve reasonable uncertainty when C inputs can be estimated well and when soil processes can be calibrated to good amount and quality of empirical data	ICBM, RothC, K-model	Although suitable for field/paddock-scale applications, estimating C input is difficult for perennial vegetation, especially pastures; rarely used below field/paddock scale; well suited for ISO 14064-2 compliant offset since "without-project" baseline can be modeled
	Ecosystem Models (FAO-LEAP level 3); soil C-N dynamics modeled vegetation growth and removal is modeled	Spatially explicit fine-scale soils data, detailed land use and management data; and daily climate data; high requirement for model calibration and validation; high data input/output complexity	Analysis is at a spatial scale of model inputs; can achieve reasonable uncertainty when the model can be calibrated to a good amount and quality of empirical data	CENTURY, DayCent, DNDC, (PaSim, APSim, etc.)	Suitable for small-scale applications where local variability can be quantified; model parameterization and testing can be done; collection of land use and verified activity data needs to be obtained; vegetation growth sub-models can be difficult to calibrate for pastures due to lack of available observations; FAO-LEAP level 3 model; well suited for ISO 14064-2 compliant offsets since "without-project" baseline can be modeled

Tier 3 Measurement	SOC amount and change by periodic measurement only	Spatial data on soils, land use, land management, vegetation, climate for stratification in carbon estimation areas, annual land management, data from periodic soil sampling; high data complexity	Spatial scale depends on sampling plan, can be coarse or very fine; capable of lowest uncertainty possible for SOC quantification	Australian carbon farming projects (farm-scale), Prairie Soil Carbon Balance Project (regional); European soil monitoring (national)	Unexpected high SOC variability can produce unacceptable high uncertainty for the sampling plan that assumed lower variability; most costly to implement; problem using for ISO 14064-2 compliant offset due to infeasibility of have SOC change for the "without-project" baseline

There are many approaches to the quantification of SOC:

- Direct measurement of SOC stocks,
- Flux measurements of emissions by flux towers and eddy covariance,
- Extrapolation of empirical models across a larger area, and,
- Process soil models - biogeochemical models that exclude simulations of plant growth
- Ecosystem models – biogeochemical models that include simulations of plant growth.

Each of these approaches can be employed independently or in some combination (see section 1.5). This report presents each quantification approach according to these categories, using examples, and assesses the relevance of each quantification approach to the desired use: to quantify and predict SOC changes in grasslands, pastures, and forage lands from the implementation of various BMPs, to enable SOC to be quantified as an ecosystem good or service.

1.1 Direct Empirical Measurement

All the models and quantification approaches described below rely on direct measurements of SOC stocks by varying degrees. The accuracy and usefulness of empirical measurements is a function of the statistical and scientific design of the sampling approach (number of samples, where they are taken relative to landscape features, stratification, sample depth(s)) and the subsequent analytical procedures (sample storage, laboratory procedures for SOC measures and bulk density). There is no commonly agreed-to, international standard for either sampling or the analytical components, and there is significant variation particularly in the sampling design of different standards and protocols (see Section 2).

Given there is no agreed-to international standard, an important paradox or balance must be considered when choosing the sampling design for direct SOC measurements to quantify SOC as an EGS – these include:

1. SOC values vary significantly within small geographies (within a meter or less), i.e. data variance is large. In order to reduce the variance and obtain a representative SOC value for a larger area more samples should be collected and processed; and,

2. The collection and processing of samples represent significant costs. There may be some efficiencies of scale, but large sample sizes are likely to be obstructively expensive.

The strategic design of a sampling plan is therefore critical. The sampling strategy refers to the selection of the locations, depth, timing, and method of subareas to sample.

Strategy development should include:

1) Definition of the purpose (area, land use, and management); this includes the quality threshold required by the market/program one is aiming for (e.g. emerging quality criteria in SOC carbon offset markets in achieving a compound uncertainty for SOC estimates of < 15% at 95% Confidence Interval (CI));
2) Description of the understanding of the causes and amount of variation and change in SOC stocks consistent with the purpose;
3) Collation and/or development of the spatial-temporal data available to use with that understanding to quantify the SOC stocks or stock changes according to the purpose; and,
4) Development of a plan in space and time that uses the data that is expected to estimate the amount of SOC stocks or SOC stock changes within an acceptable uncertainty as required to fulfill the purpose.

Risks

Relying solely on direct measurements for the quantification of SOC brings about some risks and limitations that should be considered.

First, there is no backup when relying solely on direct measurement. If the direct measurements do not provide reliable data (for example, sampling design is not representative or analytical methods are found to be erroneous or change midway, etc.) then there is no backup option – the project developer must start again. On the other hand, applying a model that does not provide reliable data (for example a serious error is found), there are normally one or more backup options for models that can be substituted without having to start all over again.

Second, when using direct measurement to monitor SOC changes over time there is a risk that the SOC change will not be detectable or significant, within a desired commercial timeframe. This is because direct measurement can only quantify total SOC stocks at any one time, and the change in SOC stocks between T_0 and T_{0+n} can often be a very small percentage (two or more orders of magnitude less) of the total stock.

Finally, there is no capability to project SOC changes over time when using direct measurement. Only a valid modeling approach can project changes in SOC over time. This can present a risk when the impact of land management on SOC is not well understood, and it can take years to detect a discernable change in SOC stocks.

Remote Sensing and Portable Quantification Tools

Beyond taking physical soil samples for off-site analysis in a lab, there are several emerging technologies for in-field and remote SOC measurements.

Direct remote sensing of bare soil by satellite, aircraft, or unmanned aerial vehicles (drones) will provide estimates of surface SOC content over an entire area (Angelopoulou et al. 2019; Croft et al. 2012; Wang et al. 2018). The accuracy is low and the utility for estimating the change in SOC has not been established. Nevertheless, where bare soil is visible from above, it will provide unique comprehensive information of SOC amount at the immediate surface. This information could also be combined with more conventional estimates to improve estimation over large areas. However, the need for bulk density estimates does not go away.

The use of portable spectroscopic analytical equipment able to perform SOC estimates in the field would greatly reduce soil handling and processing costs. However, the differing conditions (e.g. moisture content, roughness) of soil samples inherent for in-field analysis makes this less precise than laboratory spectroscopic analysis (Bricklemyer and Brown 2010; Soriano-Disla et al. 2014). Additionally, if bulk density is measured using laboratory techniques, the spectroscopic analysis can also easily be done in the laboratory and the sample condition standardized (e.g. air dry, sieved, etc.). So, in-field spectroscopic analysis will only be decidedly advantageous if bulk density is not measured. Estimating bulk density introduces much additional uncertainty to the estimates of SOC mass. Careful statistical investigation would be needed as to the measurement intensity required to estimate SOC to required confidence limits with in-field spectroscopic analysis to determine its cost-effectiveness, or even feasibility to meet accuracy requirements and market thresholds, alternative to other more conventional SOC estimation methods.

Laser induced breakdown spectroscopy (LIBS) is a promising technique for measuring SOC concentration in the field. It is based on vaporizing soil with a high energy laser and then measuring the C content based on atomic spectral signature (Cremers et al. 2001; Gehl and Rice 2007). Inelastic neutron scattering is a non-destructive (no removal of soil) in-situ method to estimate the C concentration in the soil (Wielopolski et al. 2011; Wielopolski et al. 2010; Wielopolski et al. 2008). It is potentially possible to measure SOC over large areas using inelastic neutron scattering by moving the equipment over the land surface. However, neither method is at state of development to be sufficiently accurate to replace more traditional analytical methods (Izaurralde et al. 2013).

1.2 Flux Measurement using Towers and Eddy Covariance

Another method to estimate SOC change is to continually measure the net exchange of CO_2 between the land surface and the SOC by eddy covariance. Note that a key difference from the above direct SOC measurement is the measurement unit – flux measurements measure CO_2 (and, possibly, other greenhouse gases), whereas SOC measurements measure carbon stocks at a point in the soil (and then convert to a CO_2 equivalent). Once all carbon fluxes have been quantified, including gaseous as well as lateral transfer such as harvest, manure additions, dust fall, etc. the difference in fluxes will be the net amount of CO_2 taken up by the land surface. Another important difference is that the fluxes are for an area of land rather than a point.

There are quantification challenges with the method. First and, obviously, the SOC difference is the small difference calculated from large fluxes of CO_2 to and from the land surface. Any errors in either flux will affect the accuracy of SOC difference. The location and size of the area being measured changes with wind speed and direction. So, the tower for measuring CO_2 exchange must be located in a large homogenous area that is assumed to be behaving the same. Another challenge is that the method does not work when there is an air inversion (warm area above cold air at the surface) that is most common on calm nights. During inversions, the exchange has to be estimated with other methods, such as modeling based on CO_2 fluxes on nearby nights without air inversion. Other challenges are the expense of equipment, period of equipment malfunction, removing the effects of CO_2 fluxes from farm machinery, livestock, equipment maintenance personnel, wildlife, and estimating lateral C transport (manure application, harvest), etc.

Note that measuring the efflux from the soil can be easily be done by collecting gas over the soil surface with chambers placed on the surface, but does not measure the net exchange. The flux of CO_2 into plants and then as organic C into the soil would have to be estimated by another method such as process modeling. Therefore, soil efflux measurements are used to better understand processes that can be used to improve or calibrate process models but cannot directly estimate the change in C stocks on the land.

1.3 Empirical Models

Empirical models are developed by finding the best-fit model to describe the data presented by empirical SOC observations. This method is well established and involves deriving an accurate estimate for a subarea and, based on what that subarea represents, upscaling that estimate to derive an estimate of the SOC for the entire area of interest. When the estimate is based on measurements and applied to the whole area for which the observation is considered to represent, this approach is often called "measure and multiply" since the SOC for the subarea of a few cm^2 for a soil core is multiplied by the ratio of its area to the whole area of interest. For example, to estimate the SOC for a quarter section of 64.7 ha with a single 5 cm diameter core, the area of the core (19.6 cm^2) will be multiplied by 330 million core areas in a quarter section. Another way of thinking about this is that the SOC in the larger area is a population of 330 million SOC in core-sized subareas. The core becomes a sample from the population and is sample is then used to estimate the SOC of the whole population.

Using this 'measure and multiply approach', empirical models, therefore, rely heavily on the representativeness of the empirical measurements from which they are developed to reduce the uncertainty of the model. As discussed above, uncertainty associated with empirical measurements can be improved with a greater number of samples and a stronger statistical sampling design, but this comes at a cost. Creating a SOC dataset from the ground up for the development of an empirical model is normally prohibitively expensive and time-consuming. Empirical models are therefore normally developed using existing datasets available in the peer-reviewed literature or other sources.

As discussed above, there is significant noise (inherent variability) and variation in empirical measurements over time and space, especially for SOC measurements in grasslands which are particularly diverse. Grasslands tend to be more heterogeneous regarding plant species composition, soil biota, soil type, and management, interaction of grazing animals, and tend to occur over larger areas when compared to croplands. This limits the capability of empirical models to project SOC changes over time since they are based on point measurements. Similarly, there are intrinsic limitations to the application of empirical models over different geographies, since they are developed from measurements taken at point locations. For this reason, there are few empirical models that have been developed for grassland SOC change.

The IPCC tier 1 equations are one of the few examples of empirical models for grassland SOC. These equations take into account default factors for:

- Land use – native or permanent grassland;
- Inputs for improved grassland - fertilizer inputs, species improvement, irrigation; and
- Management – degree of degradation, grazing pressure, and improvement, for three climate regimes (temperate/boreal, tropical, tropical montane).

The default factors represent the influence of management to a depth of 30cm over a 20-year period.

1.4 Process Models

Process models attempt to model various biogeochemical processes occurring in the soil to simulate reality. Process models can account for much of site-specific influences on SOC including those independent of management (weather, soil type, and initial SOC content) and those depending on management (tillage, crop sequence, pasture utilization, renovation practices, fertilization, etc.). Importantly, the major SOC process models only estimate SOC change in the upper 20 to 30 cm of soils and so measurements are needed to estimate SOC change deeper in the soil based on observed relationships between SOC change near the soil surface and that in the subsoil. The key advantage of validated process models over empirical models is that they can be used to project estimates of SOC stocks over longer time scales than measured.

Validation

A valid process model is one that generates predictions that are consistent with real-world observations within acceptable limits or errors (Refsgaard et al. 2007). This must be demonstrated over the range of soils, weather, land uses, and land use management for which they will be applied (IPCC 2006; 2019). The agreement does not need to be shown for every combination but at least the range in each should be covered. There is no agreed-upon standard as to what constitutes acceptable consistency and acceptable error – this is generally dictated by the particular market being targeted (i.e. the standard, protocol, or program/regulator in terms of EGS markets).

Calibration

Aside from the validation process to derive a valid model for the suite of geographically relevant circumstances, a further step is required to calibrate the model to the areas of the project at hand – this involves fine-tuning process model parameters to improve agreement with a calibration dataset. This is particularly common for ecosystem process models (see below). However, it is essential that the data used for validation be different from that used for calibration. The more different the validation data is from the calibration, the better the test of the validity of the model. Having a large number of different parameter sets, such as from separate calibrations to an individual site, makes upscaling uncertain since the domain limits that apply to each parameter set are uncertain. So, a single parameter set for a large area is preferred since the domain limits are broader or more representative, and can therefore be applied throughout the area for which the model is extrapolated.

The initialization of models refers to predicting the initial value of SOC after equilibration of SOC, using the calibrated parameters, and causes as much uncertainty as to the parameters (Peltoniemi et al. 2006). Typically, initialization or spin-up of the model prior to estimation of the quantified change in SOC is done for 1000s of simulated years.

Soil-only Process Models

Soil-only process models are models that represent many of the processes in the soil regarding SOC but do not represent plant growth or plant-soil-atmosphere interactions. Soil-only process models have been developed primarily for cropland situations since they require input data for the carbon inputs from plant activity. This data is relatively simple to obtain for cropland as plant growth rates, growth curves, and yields tend to be monitored; this is not normally the case for grassland systems.

Soil-only process models applied in Canada are the Introductory Carbon Balance Model (ICBM) (Bolinder et al. 2006; Bolinder et al. 2007; Campbell et al. 2007b; Kröbel et al. 2016; Lemke et al. 2010), RothC (Fan et al. 2019), Campbell model (Campbell et al. 2007a; Campbell et al. 2007b; Lemke et al. 2010; Lemke et al. 2012; Smith et al. 2013a), and K-model (Feng 2009; Li et al. 2012).

Ecosystem Process Models

Ecosystem process models include soil processes regarding SOC, plant growth, and soil-plant-atmosphere interactions. A key benefit of ecosystem models over soil-only models in the grassland context is that they include models to estimate plant carbon inputs. Additionally, ecosystem process models tend also to model additional elements such as nitrogen, as well as carbon, which is also important when external inputs and C: N interactions are not necessarily fully understood (as they might be in cropland).

Ecosystem models applied in Canada are Century (Campbell et al. 2007a; Campbell et al. 2007b; Desjardins et al. 2005; Iravani et al. 2019; Izaurralde et al. 2001; McConkey et al. 2014; Monreal et al. 1997; Pennock and Frick 2001; Shrestha et al. 2013; Smith et al. 2000; Smith et al. 2001; Smith et al. 1997; Smith et al. 2009; Smith et al. 2013a), DayCent (Congreves et al. 2015; Guest et al. 2017; Qian et al. 2019; Qin et al. 2018; Smith et al. 2013a), DNDC ((Goglio et al. 2017; Grant et al. 2004; Smith et al. 2010; Smith et al. 2013a; Smith et al. 2013b; Wattenbach et al. 2010), and STICS (Guest et al. 2017; Sansoulet et al. 2014; Smith et al. 2000).

1.5 Integrated GHG quantification

The quantification approaches described above are presented as standalone tools purely for the quantification of SOC. However, combining these approaches and integrating them with additional aspects of the ecosystem can provide added value in terms of convenient packaging of more and interacting GHG sources and sinks on grasslands. This can be particularly useful when considering BMPs that will impact aspects of the ecosystem that are directly or indirectly related to SOC. In other words, the packaging of GHG sources and sinks can minimize to some extent concerns around leakage (i.e. unaccounted for GHG emissions caused by activities shifting outside project boundaries due to project management changes) when considering the implementation of BMPs on grasslands.

The SOC and GHG emissions impacts of grazing activity are particularly relevant to grassland, pastures, and forage lands since grazing is the main land use in Canada on these lands. Therefore, the impacts of enteric methane emissions, manure management, organic and inorganic fertilizer inputs, are all aspects of land management that impact SOC. Integrated calculators for GHG quantification attempt to take into account these additional GHG sources and sinks to various degrees of linkage, complexity, and precision. It is necessary to carefully inspect the tool documentation to understand the approach used for SOC quantification. If the approach used in the tool has been well-calibrated and validated for SOC estimation for the farming situation for which the tool will be applied, then it can work very well for that application. Usually, the user cannot recalibrate the SOC quantification. Therefore, if the tool is not well calibrated or validated for the planned application, it may give very poor estimates of SOC change.

Integrated models (see Table 2) can be either proprietary or poorly documented as a package due to their complexity and as such as often a 'black box' when trying to determine the underlying models, approaches, and default parameters they use. This is significant when considering the importance of quantifying uncertainty, calibration, and validation of a model, especially when aiming to generate some type of tradeable credit. Being proprietary in nature also means that a user may be tied into the particular model once it's integrated into a user's framework or other models. Maintenance costs and accessibility to update methods, default parameters and underlying data can also be limited.

Finally, the integrated model owners have to tend to all the modeled emissions and removals so may not be able to address identified weaknesses in SOC estimation in a timely manner.

Table 2: Summary of Integrated GHG quantification tools

Name of Calculator/tool	Linkage between SOC and other sources and sinks	Transparency	Focus	Application in Canada
APSIM	Modular format allows linkage with other models. Crop Livestock Enterprise Model (CLEM) is a module for modeling grassland and livestock productivity and resource use using the APSIM platform.	Detailed reports for each crop type, module, and underlying data for defaults. Available publicly.	Cropping systems in temperate and tropical regions – grains, fibers. CLEM focus is farm resource management rather than a SOC model. Focus on farm managers, agronomists, and researchers.	Some applications of cropping modules in Canada but not for perennial crops or grasslands. There may be potential to build such a module.
Cool Farm Tool	SOC available for perennial grass and forage crops in the crop module. Crop footprints can be linked with the livestock module.	Detailed methods documents are available to members. Methods follow IPCC. The origin of some default factors is more difficult to obtain.	Whole farm assessment, ease-of-use for the farmer, but increasingly used as a supply chain GHG calculator at scale. Includes SOC stock estimates from Open Land map datasets but does not integrate this data with calculations yet. Includes Land Use Change.	Applicable worldwide since it uses IPCC methods. Does not yet include some fertilizer application methods used in North America.

Holos	The whole farm approach integrates livestock emissions with SOC.	A good set of references available publicly. Transparency of methods and underlying data and assumptions likely available to Canadian users.	Specifically designed for whole-farm assessments in Canada. More widely used by researchers and agrologists than farmers.	Developed exclusively for Canada
Canada National Inventory Report	Comprehensive for Canada is divided into subregions and then into categories and subcategories of emissions.	Methods are well documented and comparable with that of other countries	National estimates	Developed exclusively for Canada

1.6 Summary of the Quantification Approaches

Table 3: Summary of Quantification Approaches

Quantification Approaches	Effort/Cost	Main sources of error	Scalability
Direct Empirical Measurement	High – many samples required with substantial processing cost for required bulk density	Highly reliant on sampling regime and intrinsic variability in soil characteristics and management.	Careful stratification of data is required to scale measurements efficiently.
Flux Measurement using Towers and Eddy Covariance	High – expensive equipment and set up costs particularly when applied to large areas.	Equipment error, climatic conditions (inversion, dust, snow), local environmental factors (surface roughness, spatial heterogeneity, local factors impacting CO_2 flux apart from respiration in the soil).	Currently only practically appropriate for research of small areas (low towers) or of integrated value for large area (high towers).
Empirical Models	Low to Moderate – highly dependent on availability and quality of empirical data. If sufficient datasets are available, model development costs are low to moderate depending on the complexity of the empirical model.	Highly reliant on quality of underlying empirical data.	Caution is required when attempting to apply empirical models over geographies outside those from which underlying empirical measurements were taken.

Process Models	Moderate – quality biogeochemical process models require technical expertise to set up. The primary cost is calibrating and validating the model against real world-observations.	Highly reliant on the quality and thoroughness of datasets of observations for calibration and validation datasets. There is no universally-recognized standard as to what constitutes acceptable consistency and acceptable error – this is generally dictated by the user.	With high quality data on farm practices and situation as input to the model, the results from validated models can be upscaled relatively well. The depth that the model is capable should also be considered since many models estimate SOC change in the upper 20 to 30 cm only.
Integrated GHG quantification	Low to Moderate – Dependent on the individual quantification tool/calculator, data needs, and owner's business model. There is a risk of being tied into a single integrated tool/calculator.	The quantification tool/calculator may not perform accurately for the local situations it will be used but it cannot easily be adjusted to improve accuracy. Often inputs are simplified and assumptions are made to improve user experience. Transparency of underlying parameters and estimating models can be a concern.	Often developed to be applied over large scales. This can reduce the specificity of the results for the individual farm situation

2. Methods for Application for EGS quantification

2.1 SOC Change and Attribution

Attribution is connecting SOC change to a specific intervention such as a specific land management change. Estimates of SOC change based on measurement capture the integrated outcome of SOC change due to an ongoing change in management but there is no way to tease out the effects of different causes for measurement change in a given system. One way is to have a companion system of practices set aside on a plot of land, reflecting the business as usual or baseline set of practices. In fact, the basis of replicated field experiments is to separate effects due to the difference between two treatments. If one treatment is considered a control, then the difference from the control is often termed the effect of the other treatment. Effects such as weather that affect both similarly will largely cancel out. The SOC difference becomes a factor of SOC change and is considered more robust to apply to the other similar situation than to apply the change of SOC over time to a similar situation. Empirical models, such as IPCC factors, are invariably the SOC difference between one treatment and a specified reference condition.

Other than the area of small-plot experiments, it is difficult to conceive of a commercially feasible means to have a physical "control" (i.e. baseline set of practices) of land use or management that would be representative of a large area in order to actually measure the effect of different land use or management over that large area on a ranch or series of ranches. Having sufficient area and representativeness of the control, and demonstrating that the control is appropriate and managed correctly, pose major challenges. No carbon offset protocol today involving measurement of SOC change applies the quantification of the SOC change relative to a baseline.

When using process models, it is relatively straightforward to estimate the attribution for a specific effect. The model is run with all the same inputs except for the intervention. The difference is the estimate for that intervention (i.e. change in practice). In fact, many model errors cancel out when calculating the difference between the two model runs since many of the errors are the same in both runs (FAO. 2019). The control or multiple controls can be developed to separate the effect of interest.

There is emerging consensus today that the most accepted SOC quantification for large areas will be based on modeling SOC using biochemical process soil models (soil-only process models and/or ecosystem process models) with a strong and essential underpinning of measurements of SOC change to re-calibrate those models (Luo et al. 2016; Paustian et al. 2019; Smith et al. 2020; Smith et al. 2012).

The main reason the emerging best practice requires the use of estimates from both measurements and process models to derive the difference from a reference state is: the effects of the new land use and management cannot be modelled or the model cannot be validated due to a lack of empirical data, but, the reference state can be estimated with a validated model for that application. However, if the SOC change for the new land use and management can be estimated with a validated model, then employing both measurements and process models is not sensible. This is because, once using a process model to make estimates for one land use or management, the incremental costs to do the other land use or management would be much smaller than measurement. Therefore, it would be more cost-effective to model both the states with a validated process model.

One generally poor reason to use estimates from both measurements and process models to derive the difference from a reference state is to try to reduce the uncertainty of the difference by having more certain estimates from the measurement. The uncertainty of the difference is dominated by the largest uncertainty in the pair. Compared to a situation where estimates from measurement and modeling have the same uncertainty if the uncertainty of measured estimates was lowered to ½ that of the reference estimate from process modeling, the uncertainty of the difference would be reduced by only 21%. If somehow the uncertainty of the estimate from measurement could be reduced to zero, the uncertainty of the difference would be reduced by only 29%. Therefore, investing heavily in measurements to reduce the uncertainty of a difference is not likely to be cost-effective.

2.2 Standards/good practices

ISO 14064-2:2019: Greenhouse gases — Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements

ISO 14064-2:2019 specifies principles and requirements and provides standardized approach/guidance at the project level for the quantification, monitoring, and reporting of activities intended to cause greenhouse gas (GHG) emission reductions or removal enhancements. In order to have a broad and flexible application to different GHG project types and sizes, ISO 14064-2 establishes principles and specifies process requirements rather than prescribing specific criteria and procedures (see Appendix A). Environment Canada and Climate Change, along with provincial Offset Systems in Canada, all require project-level quantification conform to the ISO 14064:2 standard.

Canada (and the provincial systems) has committed to following ISO 14064 standards for quantification and verification of all GHG offset credits in compliance markets. This is an important consideration when designing a quantification mechanism for crediting SOC benefits in Canada. The following protocols do not all conform to the ISO 14064 standards. Protocols that do not conform to ISO 14064 standards are ones that do not provide an appropriate business as usual baseline according to the standard. The standard requires quantification to proceed via an apples-to-apples comparison of project scenario GHG emissions or carbon stocks, minus baseline scenario GHG emissions, or carbon stocks. In terms of application to SOC stocks to quantify SOC change over time, this means that the baseline SOC stock must be projected over time using a model, or direct measurements must be paired with a representative area where a practice change is not implemented, to estimate the baseline SOC stock at time, T_n, and enable apples-to-apples comparison to project scenario SOC stock also at time, T_n. Baseline SOC stock must therefore take into account ongoing changes in SOC stock over time with business-as-usual land management and equal meteorological/climatic impacts.

Standards such as the ISO 14064:2 standard for GHG quantification include several important rules to ensure GHG emission reductions that are credited are authentic and can be verified. Some important rules that apply in this context are:

- **Additionality:** A fundamental policy requirement of all carbon offset programs that require a project to provide 'additional' emission reductions and removals that would not have happened in the absence of the project (i.e. business as usual activity)
- **Leakage:** A phenomena whereby the reduction in emissions (relative to a baseline) in a jurisdiction/sector associated with the implementation of mitigation policy is offset to some degree by an increase outside the jurisdiction/sector through induced changes in consumption, production, prices, land use and/or trade across the jurisdictions/sectors. Leakage can occur at a number of levels, be it a project, state, province, nation or world region. Leakage happens when a GHG project causes emissions to simply shift from one place to another without the shifted emissions being included in the project emissions (note, unaccounted leakage can decrease emissions within the project and/or increase emissions within the project) .
- **Permanence:** Permanence is a criterion to assess whether GHG removals and emission capture and storage are long-term, considering the longevity of a GHG reservoir or carbon pool and the stability of its stocks, given the management and disturbance environment in which it occurs. It is applicable to sequestration projects, because they can be reversed (e.g. if a forest burns) and not applicable to reduction projects involving infrastructure changes because they cannot be inexpensively reversed (e.g. replacing Diesel generators with solar photovoltaic system).
- **Verification:** A systematic, independent and documented process for the evaluation of a greenhouse gas assertion against agreed verification criteria (e.g. ISO 14065) which is a requirement of all credible GHG programs and it involves an independent auditor verifying or certifying the emission reductions and removals generated by the project are real.
- **Double-counting:** When an emission reduction is counted twice. For example: Fraudulent activities – e.g. the same credits are sold to multiple buyers; Double claiming – two or more parties claim the same emission reduction (can happen unintentionally when multiple

mitigation mechanisms overlap); Double issuance – more than one emission reduction unit is registered for the same mitigation benefit.

- **Functional equivalence:** The standardized unit used in GHG quantification to ensure "apple-to-apple" comparisons. Emission reductions are calculated by comparing greenhouse gas emissions in the project condition relative to the baseline condition for the project or activity. In order for this comparison to be meaningful, the project and the baseline must provide the same function and quality of products or services. This is known as functional equivalence. This consistency in metrics and units of production provides an ability to quantify actual emissions reductions achieved in the project condition.

2.3 Published Protocols for SOC change for GHG

Australia Carbon Farming Initiative - Measurement of Soil Carbon Sequestration in Agricultural Systems

The Australian Carbon Farming Initiative provides a methodology to generate credits for measured increases in SOC stocks as a result of one or more new or materially different management activities, primarily pasture improvements. SOC stocks are estimated via direct measurement only, using specified soil sampling methods and laboratory techniques, or calibrated in-field sensors.

The methodology employs an innovative method of discounting credit generation for the uncertainty associated with direct measurement by generating credits for a value for which 60% of the expected SOC change values will exceed, rather than employing confidence limits as the quality criteria (like all other carbon markets in the world). Additionally, 50% of the measured SOC increase is retained in a buffer pool until the SOC measurements (minimum 1 year apart, maximum 5 years apart) have been taken that show no SOC stock loss over time (to minimize the impact of the variability of direct measurements over time) for the first two resamplings. This deduction is returned to the project developer if the SOC gained is retained for third or subsequent resamplings. For the second and subsequent resampling, the SOC is estimated from a straight-line regression equation with the amount reduced to the value with 60% of predicted SOC values will exceed. This adjustment is based on the goodness of fit to the straight-line regression, not the uncertainty of the measured value as was the case for the first resampling. This approach enables credits to be produced from a small number of samples with relatively large variability that would not be statistically justifiable in other methodologies.

Credits are sold by delivery contract, either an option for delivery or fixed delivery date. The contract also specifies the permanence obligation period – 25 or 100 years from last delivery of a credit from the project. There is a discount of 25% and 5% for a 25-yr and 100-yr obligation period, respectively, that goes into an untracked buffer. Any credits that are lost over the obligation period may be required to be paid back. This obligation is tied to the land so is obligation is for all landowners over the obligation period.

Other GHG emissions changes from the implementation of the specified practices (such as methane and nitrous oxide emissions impacts) are calculated by models and credits are subsequently generated. Note – this method does not conform to ISO 14064:2 in that it does not have a business as usual baseline. The so called 'baseline' for SOC is the initial sampling at start of the project while for other gases is the average emission for the 10 years prior to the project.

Verra/Verified Carbon Standard VM0021 Soil Carbon Quantification Methodology (2012)

This methodology describes methods for quantifying and monitoring changes in carbon accrual in, and emissions from, soils, as well as from other GHG pools and sources which may be impacted by soil focused activities. The methodology is designed based on guidance provided in the IPCC 2003 Good Practice Guidance for Land Use, Land-Use Change and Forestry. The methodology is applicable to a range of project activities designed to improve soils, including changes to agricultural practices, grassland and rangeland restorations, soil carbon protection and accrual benefits from reductions in erosion, grassland protection projects, and treatments designed to improve diversity and productivity of grassland and savanna plant communities. Soil carbon is measured in both the baseline and project scenarios using the combination of measurements, published emission factors, and soil carbon prediction models. The DNDC model is used only for quantifying the methane and nitrous oxide emissions. The risk and degree of impact of any possible uncertainties or variations in actions or conditions, and the resulting range of uncertainty in the value of the variable at each time point are considered in this methodology. This methodology requires significant level of technical ability and has huge data requirements for estimation and projection. To date, given the complexity of the methodology, not a single project has been registered with Verra (including the project developer who brought the methodology forward).

Verra/Verified Carbon Standard VM0026 Sustainable Grassland Management (2014)

The methodology provides procedures to estimate the GHG emissions reductions and removals from the adoption of sustainable grassland management practices, such as improving the rotation of grazing animals between summer and winter pastures, limiting the timing and number of grazing animals on degraded pastures, and restoration of severely degraded land by replanting with perennial grasses and ensuring appropriate management over the long-term. The methodology quantifies emissions reductions and removals from increases in SOC stocks and reduction of non-CO2 GHG emissions. Where biogeochemical models can be demonstrated to be applicable in the project region, they may be used in estimation of soil carbon pool changes. Where such models are not applicable, the methodology provides guidance for estimation of SOC pool changes using direct measurement methods. The methodology uses a project method to determine additionality and the crediting baseline. Soil carbon is a major pool affected by changes in grassland management practices. In this methodology, proponents may either make direct measurements of SOC, or use a modeling approach. The methodology requires that all parameters used to estimate emissions and removals are conservative. Uncertainty is considered depending on the situation and approach used at each time point and deductions for uncertainty are applied following the procedures set out in the methodology. The methodology follows a very conservative approach and has huge data requirements for estimation of SOC pool changes. To date, given the complexity of the methodology, not a single project has been registered with Verra (including the project developer who brought the methodology forward).

Verra/Verified Carbon Standard VM0032 Methodology for the Adoption of Sustainable Grasslands through Adjustment of Fire and Grazing (2015)

This methodology quantifies the GHG emission reductions and removals from activities that introduce sustainable adjustment of the density of grazing animals and the frequency of prescribed fires into an uncultivated grassland landscape. Projects may rely on measured or modeled approaches. In measured approach, emission reductions are quantified following a period in which enhanced soil sequestration and/or reduced methane emissions can be demonstrated. In modeled approach, emission reductions are quantified using a validated model after demonstrating management activities, which are known to sequester carbon and/or reduce methane emissions, have been implemented. Reduced emissions from sequestration and reduced methane emissions associated with these activities are then estimated by models with acceptable precision which have been validated for the project and re-calibrated at regular intervals thereafter (5-10 years, depending on the productivity of the site). Modeled approaches have higher uncertainty due to the uncertainty in the parameters used to calculate emissions and removals and the uncertainty in whether model calculations actually describe changes in sequestration and reduced emissions. The VCS Standard requires that uncertainty be calculated on the basis of the full width of the 95 percent CI expressed as a percentage of the estimate of each emission or removal. IPCC Guidelines recommend 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. Only one project is registered to date in Kenya where Estimated Annual Emission Reductions will be 1,797,493 VCUs.

More information on the other protocols and how they address other critical offset criteria defined in the standards is given in Appendix B.

2.4 Emerging Standards, Guidelines and Protocols

Draft Climate Action Reserve Soil Enrichment Projects Protocol

The Climate Action Reserve's draft Soil Enrichment Protocol requires direct measurement of SOC to establish baseline soil carbon stocks, and to validate modeled SOC stock changes throughout the carbon offset project at a minimum 5-year interval. The protocol requires statistical uncertainty associated with the sampling method to be quantified; this uncertainty is then used to moderate the carbon offset credits generated from the project. The protocol requires minimum standards for soil sampling and laboratory analysis. Sampling design must employ stratification (pre or post, based on geographical, climatic, and/or land management variables), with a minimum of 3 sample points per stratum and a minimum sampling depth of 30cm (recommended at least two depth increments to 100cm depth, and at least two depth increments if the model being used is not capable of projecting SOC changes below 30cm). Minimum standards for lab analysis are also outlined: drying of samples within 48 hours or refrigeration, analysis of fine fraction (<2mm) only with aggregates broken by hand, corrections to bulk density for the coarse (>2mm) fraction (often called stones or rocks), and analysis by dry combustion or spectroscopic techniques (loss on ignition and Walkley-Black methods are excluded).

The CAR SEPP accepts empirical models that are publicly available, peer-reviewed, able to support the repetition of model simulations, incorporate one or more input variables that are monitored ex-post, and are calibrated, validated and verified according to CAR's standards. The protocol allows the recalibration and/or revision of models as long as the changes are applied to the baseline as well as the project scenarios. See Appendix B.

C-Sequ: Project of draft guidelines for the calculation of Carbon Sequestration for the Dairy cattle sector

C-Sequ is attempting to enable soil carbon sequestration benefits to be accounted in Life Cycle Analysis accounting for the dairy sector. This draft guidance provides recommendations for when and how to account for farm-level carbon sequestration in practical LCA, and attempts to merge the fields of LCA and GHG project-level accounting through application of an additional accounting step in LCA methodologies.

Attribution, allocation, permanence, ex-ante vs. ex-poste accounting, and quantification of SOC stocks or changes are key issues that will are being tackled. The approach provides recommendations for evaluating if carbon sequestration can be included in the assessment being performed, how to select an inventory and characterization approach that is aligned with goal and scope of the assessment, how to obtain inventory as stoichiometric CO2 given the selected approach and how to characterize inventory such that it can be accounted in the metric of CO2eq.

The main inventory collection types that are considered in the Guidance are:

- Empirical SOC models (e.g. IPCC Tier I and Tier II models) which can easily be used to obtain the net change in SOC after a land management or land use change and can be easily used for an ex-post or ex- ante approach.
- Process-based SOC models (e.g. RothC, Century SOC models) which are usually more advanced and precise models which can consider more parameters. These models tend to be useful to estimate the fraction of carbon that stays in the soil through time following an assessment year for an ex-ante approach. One could use these models for an ex-post approach, but it is less intuitive to perform and interpret.
- Measurements (e.g. SOC samples)
- Allometric equations for trees and hedges

The Gold Standard - Draft Soil Organic Carbon Framework Methodology

The Gold Standard's draft SOC Framework Methodology defines the high-level requirements and guidance applicable to SOC quantification for all subsequent modules which are specific to a certain activity (i.e. implementation of land management or agricultural practices to achieve avoidance of emissions as well as sequestration of carbon in the soil).

The SOC methodology provides three approaches for the quantification of SOC:

1. Direct measurements to document baseline and project SOC stock levels. This is the preferred, primary method of SOC quantification in the standard, but incurs the risks and limitations outlined in the above section on Direct Measurement (see 1.1 Direct Empirical Measurement).
2. Peer-reviewed publications (models) to quantify baseline and project SOC stock levels. This approach incurs deductions for uncertainty of the models employed. Some of the proposed validation criteria will be difficult to implement in practicality.
3. Apply default factors to quantify SOC changes, relating to the general methodology described in the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019) using tier 2 level approach (see Table 1) whenever possible.

The quantification of the baseline as described in the draft document does not conform to ISO 14064 standards since the baseline SOC stock is measured before the practice change is implemented, i.e. it is a static baseline taken at time, T_0. To conform to the ISO 14064 standard, the baseline should be projected with the ongoing business as usual land management and climatic inputs, or paired with a site where practice changes are not occurring, i.e. a projected baseline to estimate SOC stock at time, T_n, to subtract from the project scenario SOC stock also at time, T_n. The standard instead recommends subtracting baseline SOC stock at T_0 from SOC stock in the project at T_n. Other potential issues include the lack of deductions for uncertainty associated with direct measurement – as described above direct measurement incurs uncertainty in the estimation of SOC stocks as well as the use of models. There are also issues with the boundary/scope of emissions sources regarding the inclusion of grazing emissions but the exclusion of enteric methane emissions.

2.5 Summary

Table 4: Summary of Protocols Applying SOC Quantification for EGS Markets

Protocol	Methodologies (Measurements/Models)	Data and monitoring requirements	Uncertainty	Feasibility
VM0021 Soil Carbon Quantification Methodology	Combination of measurements and models	Significant level of technical ability, significant data requirements for estimation and projection.	Not mentioned	Not feasible due to technical and data requirements.
VM0026 Sustainable Grassland Management	Combination of direct measurement methods and biogeochemical models	Very conservative approach, significant data requirements for estimation of SOC pool changes	Uncertainty depends on the situation	Not feasible due to technical and data requirements, and conservative credit generation.
VM0032 Methodology for the Adoption of Sustainable Grasslands through Adjustment of Fire and Grazing	Rely on measured or modeled approaches	Depends on the methodology	Monte Carlo simulations/ weighting uncertainties according to the magnitude of emission or removal	Feasible

Australia Carbon Credits (Carbon Farming Initiative-Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018	Direct measurement through sampling analysis	Depends on sampling design	Standard error calculated based on sampling round	Feasible
Draft Soil Enrichment Protocol: Reducing emissions and enhancing soil carbon sequestration on agricultural lands	Both direct measurement and models	The direct measurement is used to back-calculate the previous year's SOC stock using the same model and to subsequently modify the model to fit the empirical measurements.	Uncertainty deductions depends on the uncertainty size	Can be problematic due to discount for model uncertainty
C-Sequ: Project of draft guidelines for the calculation of Carbon Sequestration for the Dairy cattle sector	Empirical SOC models, Process-based SOC models, Measurements, Allometric equations for trees and hedges	Unknown - draft	Not mentioned	Unknown - draft

Soil Organic Carbon Framework Methodology- Gold Standard for The Global Goals	On-site measurements and using tier 1 & 2 level approach	Direct measurement preferred. Extent not yet known – draft.	The project proponent shall use a precision of 20% of the mean at the 90% confidence level as the criteria for accuracy of total SOC change calculation.	Preference for direct measurement only, and discounting for use of models means feasibility may be restricted.

3. Uncertainty

Uncertainty is estimated from the agreement with observed SOC and the uncertainty of model inputs such as weather, crop production, soil texture, etc.(Beven 2016; Gibbons et al. 2006; Huang et al. 2017; Juston et al. 2010; Miehle et al. 2006; Monni et al. 2007; Ogle et al. 2007; Panda et al. 2008; Refsgaard et al. 2007; Uusitalo et al. 2015; Wang et al. 2011; Xiong et al. 2015). The uncertainty of the observations also enters into the model uncertainty (Beven 2008; Chen et al. 2018; Gottschalk et al. 2007; Haan et al. 1995)

3.1 Measurement

The critical factor for measurement is the variability, typically represented by the standard deviation, assuming a normal distribution. Classical statistics is concerned about the probability that the observed difference could be due to chance alone. The greater the variability, the greater the chance of observing a difference is due to chance. The Figure 2 shows the minimum detectable difference, detectable with no more 5% probability of it, being due to chance. That detectable difference as % of SOC stocks in grasslands gets smaller (i.e. measurement becomes more precise) as the area measured decreases or the number of samples increase (Maillard *et al.*, 2017). This is for an unstratified situation - with good stratification (as discussed previously) it is possible to increase the precision for large areas to that for small areas.

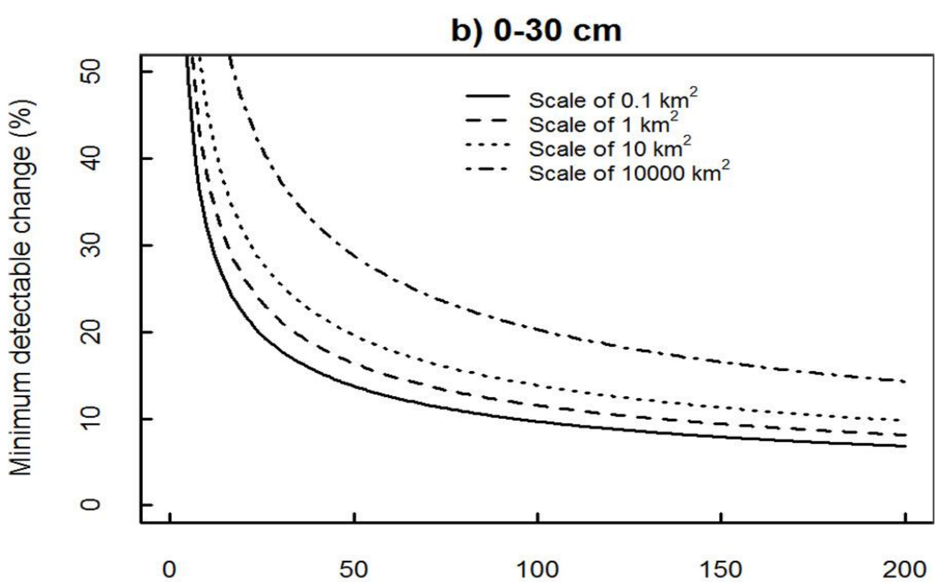

Figure 2: Sample vs minimum detectable change (%)

However, to meet typical high-quality determinations according to classical statistics (e.g. 5% chance of set difference being due to chance alone and 90% probability of detecting a set difference) takes either a large amount of sampling for SOC at farm/ranch scale or requires generalization to the extent that regional trends in SOC change are measured with no resolution for farm-specific management. Therefore, in practice, offset protocols either just assume that observed mean change is valid regardless of the probability of occurring by chance or, for the Australian Carbon Farming Initiative for the first sampling, discount the amount by the measurement uncertainty.

However, even if no discount to the SOC credits occurs, it is still relevant to do an investigation of the probability of measuring a SOC change much less, including a SOC loss, than the expected SOC gain so to set the sampling intensity to reduce that particular risk to a value the offset project owner accepts. That risk also goes the other way - the greater the chance of underestimating the unknown SOC gain, the greater the chance of overestimating the unknown SOC gain. Protecting against the risk of measuring a lower SOC change than the unknown actual change is also relevant if there is a discount. But, with a discount, there is also the need to investigate the trade-off between intensity cost of sampling and size of the error, because having an acceptable discount is also relevant even when, by chance, the measured change is at or above the unknown actual SOC gain.

3.1.1 Impact of method of SOC determination

Dry combustion to determine SOC concentration is the 'gold standard' and so provides the least uncertainty for individual samples, but there is keen interest in less expensive methods as discussed previously. Uncertainty evaluations will need to be considered in these cases.

SOC quantification from whole area via remote sensing

Direct remote sensing of bare soil by satellite, aircraft, or unmanned aerial vehicles (drones) will provide estimates of surface SOC content (Angelopoulou et al. 2019; Croft et al. 2012; Wang et al. 2018) over an entire area. The accuracy is low and the utility for estimating the change in SOC has not been established. Nevertheless, where bare soil is visible from above, it will provide unique comprehensive information of SOC amount at the immediate surface. This information could also be combined with more conventional estimates to improve estimation over large areas.

Visible, Mid-infrared and near infrared Spectroscopy

Spectroscopy using visible (Vis), near-infrared (NIR) and mid-infrared (MIR) has proven to be a rapid way to estimate SOC concentration (Bellon-Maurel and McBratney 2011; Soriano-Disla et al. 2014; St. Luce et al. 2014). A model of the observed relationship of the spectral reflectance across the different combinations of Vis, NIR and MIR bands and known the SOC from dry combustion is developed. That model is then used to estimate the SOC based on measurements of reflected spectral signature for other soils. The data set of soil with known SOC from which the model is developed is called the calibration set, training set, or soil library. It is essential that the model be validated with another set of soil with known SOC determined by dry combustion. This is termed the validation set. The calibration set needs to cover the range of soils and soil states (dry, moist, ground, unground, etc.) for which it will be modeling SOC for new soils. The best validation sets include soils that were not close to those used in the validation set such as from a different part of the field or an entirely different field from what soils in the calibration set.

There is uncertainty with the model of SOC concentration related to spectral reflectance. Therefore, to have equal detection ability as conventional dry combustion will require more samples be analyzed. Therefore NIR-MIR spectroscopy is most attractive when making many thousands or more measurements in a project. The requirement to have a sufficient number of analyzed soils in the calibration and validation sets projects makes projects with only a few thousand or less makes the more accurate dry combustion analysis more attractive.

The greatest challenge with spectroscopy is bias in the estimate made for soils dissimilar to the those in the calibration set (Bellon-Maurel and McBratney 2011). There is little bias for soils that are very similar, such as within the same field as the calibration set. Thus, a good calibration data set that includes dissimilar soils such as would be subject in analysis in the project will help identify the potential for bias but cannot estimate the actual bias for soils dissimilar to those in either the validation or calibration sets. Having as wide as possible range of soils in the calibration set also provides some protection against bias. The best protection is to ensure that soils similar to those whose SOC will be estimated are always included in the calibration set and validation sets. The Australian carbon farming initiative protocol accomplishes this because it requires that at least 20% of samples in a stratum be included in the calibration set and at least a separate 10% of the samples in a stratum be included in the validation data set. Bias in space is not necessarily a problem if the primary goal is SOC change rather than SOC stocks. This is because most of the spatial bias will cancel out for the same soil between estimates at different times. Changing bias with time, however, would be a serious problem since the bias would not cancel out between SOC estimates made at different times. Although it is not been a topic of investigation in the literature, after many years of a new land use and management, the relationship of the spectral signature to SOC may change because the nature of the SOC changes. Therefore, it would be good practice to establish recent calibration set to check the accuracy of the model over, at least, decadal times scales.

Another challenge is that most accurate estimation is when the condition of the soil sample has to be the same for the calibration set and soils to be analyzed (Martin et al. 2002). The Australian carbon farming initiative protocol accomplishes this because it requires that all samples be air dry and sieved for all soils: validation set, calibration set, and those soils whose SOC will be estimated.

The use of portable spectroscopic analytical equipment make that estimates in the field would greatly reduce soil handling and processing costs. However, the differing conditions (e.g. moisture content, roughness) of soil samples inherent for in-field analysis makes this less precise than laboratory spectroscopic analysis (Bricklemyer and Brown 2010; Soriano-Disla et al. 2014). If bulk density is measured using laboratory techniques, the spectroscopic analysis can be easily done in the laboratory. Thus, in-field spectroscopic analysis will only be decidedly advantageous if bulk density is not measured. Estimating bulk density introduces much additional uncertainty to the estimates of SOC mass including the potential for general bias. Careful statistical investigation would be needed as to the measurement intensity required to estimate SOC to required confidence limits with in-field spectroscopic analysis is cost effective, or even feasible to meet accuracy requirements, compared with other more conventional SOC estimation methods.

Other methods for determining SOC

Laser induced breakdown spectroscopy (LIBS) is a promising technique for measuring SOC concentration in the field. It is based on vaporizing soil with a high energy laser and then measuring the C content based on atomic spectral signature (Cremers et al. 2001; Gehl and Rice 2007). There are portable units for in-field determination although usually done in the lab. Inelastic neutron scattering is a non-destructive (no removal of soil) in-situ method to estimate the C concentration in the soil (Wielopolski et al. 2011; Wielopolski et al. 2010; Wielopolski et al. 2008). It is potentially possible to measured SOC over large areas using inelastic neutron scattering by moving the equipment over the land surface. However, neither method is at state of development to be sufficiently accurate to replace more traditional analytical methods. (Izaurralde et al. 2013).

3.2 Modelling

There is minimal use of empirical models for SOC change with the exception of the IPCC Tier 1 approach. The reason is that is difficult use regionally specific empirical factors to estimate change over time because they cannot be reliably extrapolated. They are most usually used for estimating change in SOC in the past, with that time being within the time frame of empirical observations used to derive the factor. An example would be for use in a carbon footprint of a cattle production for a particular year not in the future. If there were relevant measurements that gave the change for the forage and grazing land similar to the cattle production under investigation, then an empirical factor is used to estimate the effect of SOC change on the carbon footprint. However, that empirical factor would not be used to estimate how the carbon footprint for cattle production will change over time.

There is growing consensus that most accepted SOC quantification for large areas will be based on modeling SOC using biochemical process soil models (level 2 or 3) with a strong and essential underpinning of measurements of SOC change to re-calibrate those model (Smith *et al.*, 2012; Luo *et al.*, 2016; Paustian *et al.*, 2019; Smith *et al.*, 2020). The model can account for much of site-specific influences on SOC including those independent of management (weather, soil type, and initial SOC content) and those depending on management (tillage, crop sequence, pasture utilization, renovation practices, fertilization, etc.). Importantly, the major SOC process models only estimate SOC change in the upper 20 to 30 cm of soils and so measurements are needed to estimate SOC change deeper in the soil based on observed relationships between SOC change near the soil surface and that in the subsoil.

Uncertainty of modelling

Table 5 shows some estimated uncertainties for models for situations including grazing and forage lands. Some uncertainties for situation that include grazing and forage lands for models that have been used in Canada.

Table 5: Some uncertainties for situation that include grazing and forage lands for models that have been used in Canada

Model	Application	Where	Fit and uncertainty	Notes	Reference
DNDC	Tame Grassland with pig and cattle slurry at different rates, simulation to 50 cm	Ireland	Validation: RSME=8.6 about 12% of stocks	SOC below 15 cm underestimated for some treatments	(Khalil *et al.*, 2020)
Century	Native grassland across Alberta, grazed and ungrazed	Alberta, across whole province	Prediction: SOC 11-25% uncertainty regionally	Above-ground biomass included actual data and estimated from remote sensing, validated with 0-5 cm SOC measurements	(Iravani *et al.*, 2019)
RothC	National C change to 20 cm including pasture and forage	Canada	Prediction: 3-17% of regional stocks based on C input		(Fan *et al.*, 2019)
Century	National C change in SOC	England and Wales	RMSE : Arable cropland 0.22 t C/ha Managed grassland 0.50 t C/ha, Seminatural grassland 2.16 t/c/ha	Achieved correct direction 100% of time for seminatural grassland but only 60% for managed grassland and 55% for cropland	(Sakrabani and Hollis, 2018)
RothC	Annual and perennial pasture	Australia	Validation: RMSE 2.2 t C/ha or about 5% of SOC stocks	Had good pasture growth measurements to estimate C input	(Liu *et al.*, 2011)

EPIC (Century based)	Set-aside grass and alfalfa with grain crops	US great Plains and Alberta	Validation: Approximately 20% of SOC		(Izaurralde *et al.*, 2006)
Century	All agricultural land in European Union	Europe	Prediction: less than 36% of SOC stocks 50% of time; 10-60% effective range		(Lugato *et al.*, 2014)

From Table 5, we can see that models can obtain uncertainties in the range of 10-40% of SOC stocks for grazing and forage lands. This would be the uncertainty of detecting change by modeling SOC. When taking the difference between two model scenarios, such as baseline versus offset project, there is a high correlation of errors for the two model scenarios, particularly when there are large deviations from measured (those large deviations are typically shifting in the overall SOC level and occur in both scenarios). This correlation reduces the uncertainty of the modeled difference. Therefore, it should be generally possible to have uncertainties of modeled difference similar to that of SOC stocks for one scenario, within about 10-30% of SOC stock. It would depend on the sampling intensity how such uncertainties would compare to those from measurement. Without doubt, measurement can produce more accurate and precise estimates of the difference. The uncertain measurements also affect the uncertainty of models since the measurements are used to both to calibrate the model and evaluate model uncertainty.

Part Two: Approaches and Recommendations

4. SOC Change to be Measured

When considering measurement approaches it's important to consider what SOC change is to be measured:

1. Overall SOC change and effect on atmosphere since t_0 – this considers the SOC change from a fixed SOC stock at a point in time at which the management change is implemented. This case does not include changes that would have occurred over time without the management change.(see Figure 3)

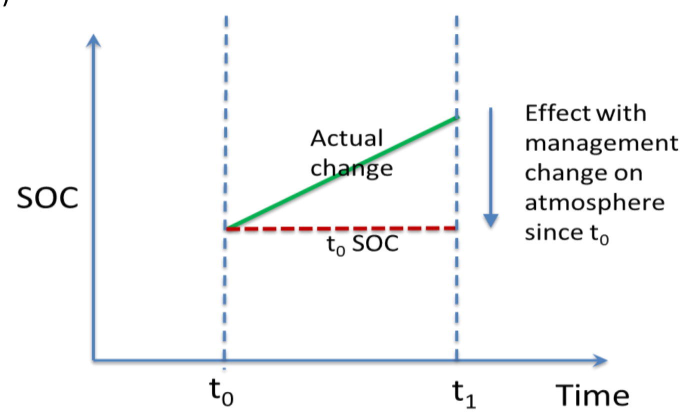

Figure 3: Different types of SOC Change

2. SOC change is limited to the effect of a management change only – this considers a business-as-usual (BAU) baseline where an assumed background rate of SOC change is included in the quantification so that the SOC change is only due to the management change. (see Figure 4)

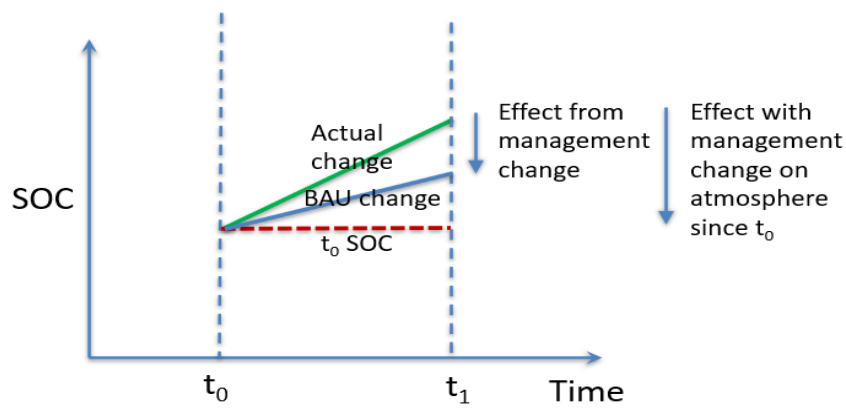

Figure 4: Overall SOC change and effect on atmosphere since t_0

4.1 Overall SOC change and effect on atmosphere since

Measuring the SOC change from a point in time when a management change is implemented (t_0) is relatively straightforward (see Figure 4). SOC changes due to weather and climate change influences are inherent to the measurement. There is no comparison to a set of business as usual practices or baseline case, and it can be difficult to determine whether a SOC change is due to human or natural influences. For example, re-establishment of a pasture on degraded cropland would generally cause SOC to increase regardless of the management of that pasture. Existing datasets show that long-term pastures can alternate between carbon sink and source, influenced by variables such as weather, climate, land use, and management.

The Australian Carbon Farming Initiative is based on this approach though most carbon markets require comparison to a business-as-usual baseline to develop offset credits specifically from the implementation of a management change.

4.2 SOC change limited to the effect of a management change only

Generally, the most accepted SOC change for transactable credits within EGS markets is the SOC change due to a management change only. This necessitates subtracting the Business-As-Usual (BAU) SOC stock (see Figure 5). It's important to note that with a BAU baseline, it is possible to have a C credit even if SOC decreases due to changing weather patterns, providing the BAU decreases more (see Figure 6). In this way the project can manage the risk of inherent weather changes that may look like a loss, but it is an avoided loss (i.e. credit) compared to the loss that would have occurred under the business as usual scenario (i.e. the 'with project' management change loses less than the BAU). Modeling the BAU SOC allows for project developers to manage this weather-induced risk, which is typically not economically feasible to do with measurement.

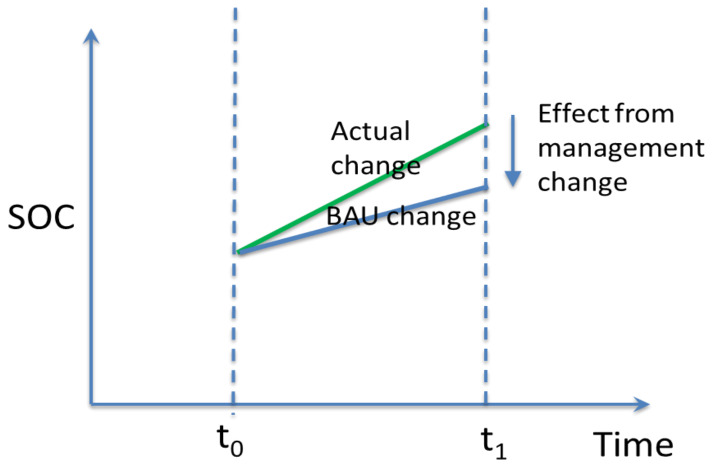

Figure 5: SOC change limited to the effect of a management change only

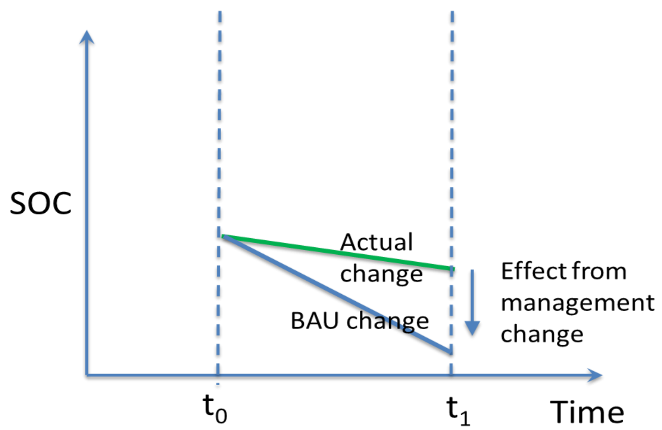

Figure 6: SOC increase due to management despite overall SOC decrease

5. Measurement and Modelling Approaches

There are four main approaches to SOC quantification for farms/ranches which are being considered by emerging protocols/methodologies:

1. Empirical factors
2. Measurement only
3. Hybrid of 'modeling and with-project measurement'
4. Modeling supported by monitoring (measurements)

5.1 Empirical Factors

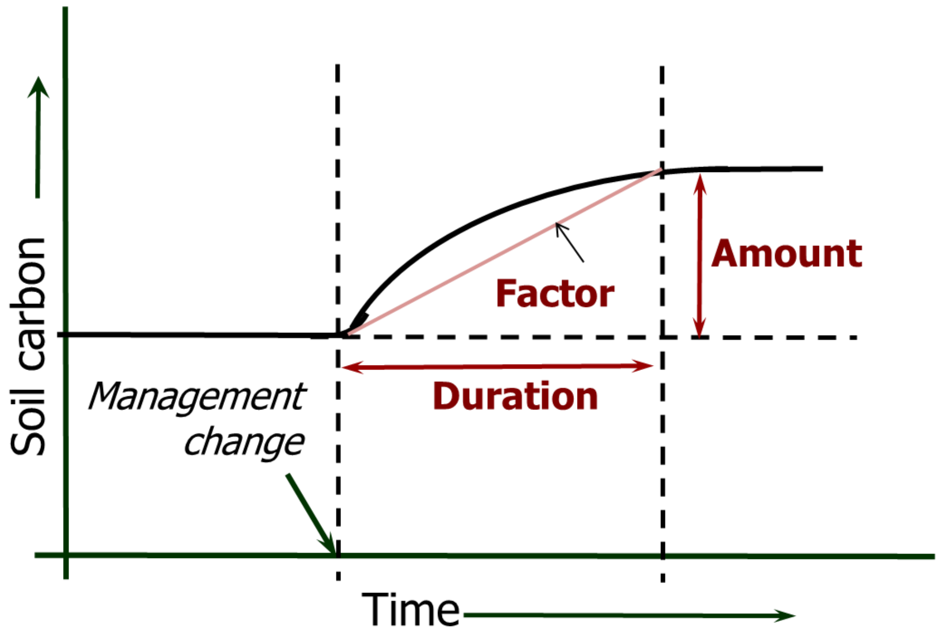

Figure 7: Graphical representation of derivation of empirical factors

Empirical factors are simplified representations or models which can be applied to an appropriate time and area to estimate SOC change. Factors are derived from observations or validated process models for various management practices and locations, depending on the level of detail and rigor required. It is feasible to derive factors from a management change comparative to a business-as-usual scenario, and apply those factors to a point in time that a management change is implemented (see Figure 7). Empirical factors are also simple to implement and understand.

However, there is often a lack of suitable data from which to derive factors especially for forage and pastureland, and management changes can be difficult to define given the large variability in land management across diverse landscapes. It can therefore be difficult to implement empirical factors at scale to the rigor required for transactable EGS credits.

5.2 Measurement only

This option includes only direct measurement of SOC stocks from soil samples to determine SOC change. Grazing and forage lands will require expensive sampling due to inherent variability. Grazed areas of

Canada tend to be on classes of land with limitations for annual cropping, and as such have more topographical, climate and soil challenges – factors that all-cause more variability.

Using a real case scenario (see Figure 8), with 16 strata per ranch, and a quality threshold of a 90% confidence limit for uncertainty (not as stringent as the emerging carbon offset marketplace requirements), the number of samples approaches 30 per strata, or 480 per ranch to approach the required mean difference of SOC change of 3 t C/ha (100%). If at least 50% of real difference is required to pay for the measurement, it's unlikely the project developer will be able to turn a profit, especially after paying for measurement costs.

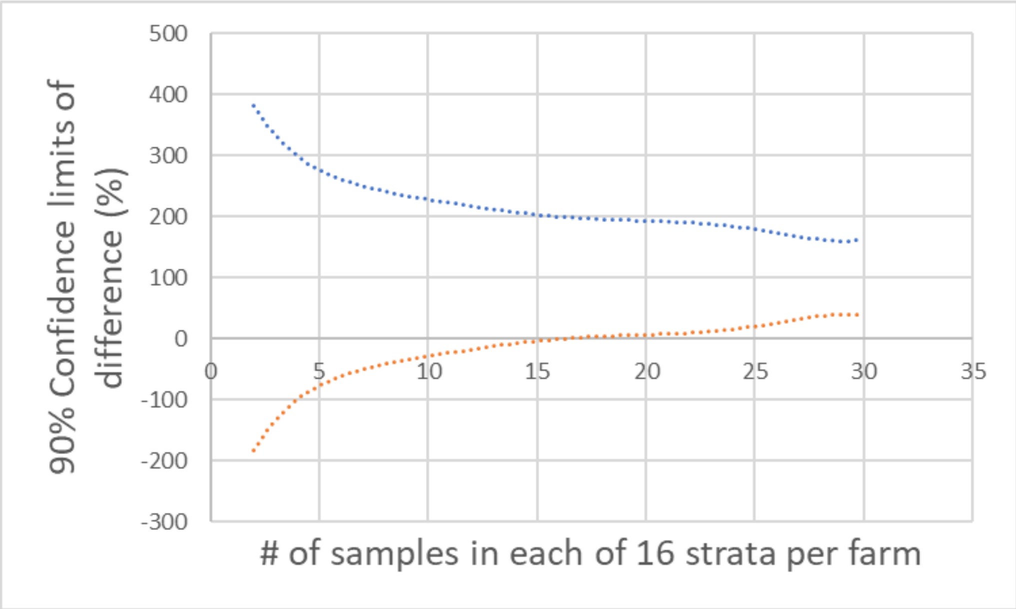

Figure 8: 90% confidence limits of difference (%) vs number of samples in each of 16 strata per farm. Real difference of 3 t C/ha (=100%).

A significant number of samples is required to get the expected results, and if not sampled appropriately, the carbon credits will be either be discounted heavily or be subject to penalty, depending on the marketplace.

5.3 Hybrid of with-project measurement and modeling

An emerging practice in developing marketplaces are hybrid approaches which consider project direct measurement and modeling. In these approaches, the BAU SOC change is modeled through well validated models and carbon credits are issued based on modeled estimates of 'with project' SOC change. Periodic soil carbon measurements (every 5 years) are used to "true-up" modelled results (see Appendix B). New observations are used to improve the calibration of the model to better estimate SOC for the with-project scenario and the BAU SOC or the ensuing five-year project period. This recalibration approach requires better quality data than is probably economically feasible to generate at farm scale from potential sale of C credits and will be challenging for project developers to meet.

Further, if the 5-year true-up measurements show that model predictions were overpredicting SOC change and more carbon credits were issued than were 'true' – then the project developer may have to pay back carbon credits. This is all predicated on the assumption that measurements are 'true' without uncertainty and models are inaccurate to varying degrees.

It's entirely possible and highly likely that the 'true-up' measurements may have so much inherent uncertainty that the true up becomes suspect as well. Very little guidance exists on how to do the true-up approach and even the model developers are not sure how to advise on this approach. In practice, the hybrid approach will be very challenging and uncertain. The draft Climate Action Reserve Soil Enrichment Project Protocol and Vera's Improved Agricultural Land Management Methodology are based on this untried method (Appendix B).

5.4 Modeling only with measurement support

This approach is similar to Option 2, but rather than relying on project developers to conduct the intensive sampling that is required to generate high quality datasets to validate and true up models, this method relies on modeling to quantify the SOC change but uses measurement support by way of a well-established network of monitoring sites. This approach proposes establishing a set of key 'sentinel sites' across the project domain, generating high-quality validation data to cover a wide range of practices, land types, and weather for which the model will be applied. It is not necessary to pick "representative" combinations of practices, land types (landform, soil texture, initial SOC), and locations (climate/weather) for calibration but pick a range of combinations that covers the breadth of practices, land types, and locations for which the model will be applied. During the SOC change quantification process, the approach will require some on-going measurements to ensure that the model remains validated. The overall cost of this approach will be low, and this will be a versatile approach. Carbon credits can be issued annually based on model estimates which are supported by this network of measurement sites.

6. Recommended Roadmap Option

6.1. Preferred option

With a few exceptions, most EGS markets and the buyers of the credits want to credit only the gains achieved specifically by a management change or intentional human intervention. There is also the consideration that the preferred approach should be able to consider the impacts and interactions of several management interventions over time. To align with market trends and the ISO 14064-2 standard, it is recommended that the quantification approach for SOC change takes into account a business-as-usual scenario.

Given this, the need to control costs, and the likelihood of implementing several management interventions over time, a measurement-only approach is not recommended. Empirical factors are unlikely to meet the rigor required by most marketplaces and credit buyers, especially given the lack of current datasets and limited scalability.

To ensure SOC changes are due only to one or a combination of several management interventions, take into account uncertainty, and are applicable at scale, a hybrid modelling and measurement approach is recommended (see Figure 9). To implement this approach at minimal cost and to maximise efficiency so that land managers can benefit from carbon offset and/or market advantages of a lower carbon footprint from increasing SOC, it is recommended that a monitoring strategy for a network of sites be developed to underpin quantifying SOC change with well validated models. Model scenarios are developed over time and these scenarios are validated against high-quality measurements from the observation network.

As a result of the Process undertaken in this Project, the Technical Advisory Group (see Appendix D: Technical Advisory Group (TAG)) and Stakeholder Feedback (see Appendix E: Summary of the project activities) resulted in the Proposed Strategy outlined in Section 6.2 below and in the subsequent sections. The process and groups/organizations involved in the development of this Roadmap can be found in Appendix E of this report. All feedback and comments are summarized and collated in the Appendix E.

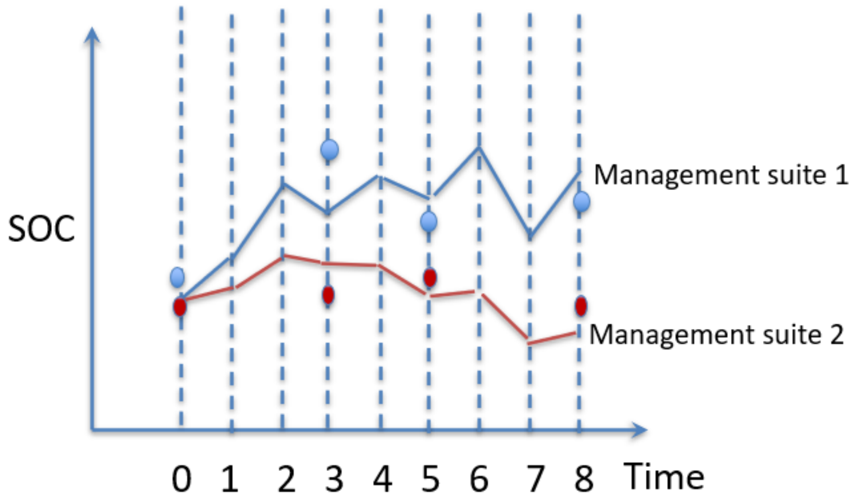

Figure 9: Recommended Approach - Model scenarios over time and validate against measurements from observation network (the business-as-usual would be on measurement suite).

6.2 Basic Features of Proposed Strategy

The proposed strategy uses process models of SOC dynamics to estimate SOC stocks for the with-project case and for the BAU baseline case, and their change from farm-specific situations. The models are underpinned by an observation network that project developers or platforms can use to validate and calibrate select models for estimating SOC change. The observation network would generate measurements from deployed BMPs and baseline situations, desirable to the geographies covered. The Canadian Forage and Grasslands Association, as well as IMWEBs, has a number of BMPs that have been identified through collaborative consultation and are candidates for implementation on these sites. In addition, the observation network can employ current and historical vegetation analysis and other useful remote sensing data layers as from inputs into the observation dataset (see Figure 10).

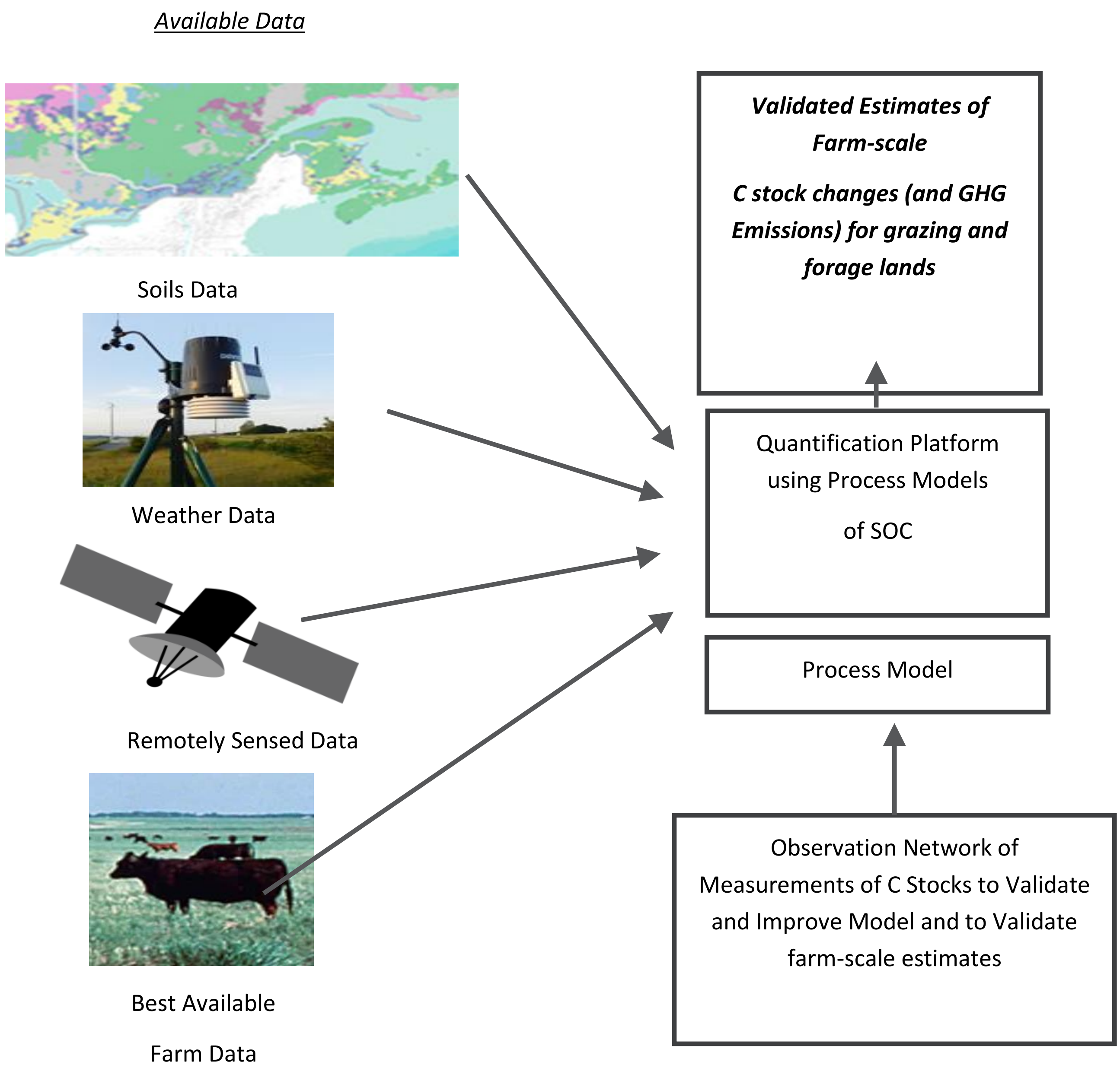

Figure 10: Structure of recommended approach

The proposed strategy fits two general applications: 1) general estimates of SOC given available data on the state and management of the grazing and forage lands, and 2) farm- or ranch- specific SOC change so that the livestock industry can obtain value and credit for SOC increases on grazing and forage lands. The roadmap describes a system to provide estimates of SOC change at the field or paddock level by modeling from input data. Remote sensed data, and already available data on soils, landscapes, and weather will be used. The detail of the farm-specific data will determine the precision and applicability.

To capitalize on farm- or ranch- specific offset or low-carbon footprint market opportunities, land managers would have to supply information on their specific management and allow on-farm measurements, as necessary. To provide national and regional estimates of SOC change, it will not be feasible to have detailed data provided annually by farm managers. Therefore, the farm management data for national/regional purpose will be more imprecise as it will be derived from surveys, inferred from remote sensing, and expert opinion. The SOC estimates from such data will be relevant to the general situation but will not necessarily be accurate for individual fields or paddocks, or to individual farmers or ranchers.

6.3 Description of the Canadian Forage and Grassland Observation Network – Guiding the way to profitable natural climate solutions

The strategic observation network is the essential data repository of the roadmap on SOC change. For this carbon roadmap, the data will be used to identify effective and economical management of forage and grassland that maintain and/or increase SOC as a natural mitigation of greenhouse gases (i.e. guiding the way to profitable natural climate solutions). The data will enable the development of the relationships of SOC change with the management, remotely sensed data, and specific land and weather situation of grazing and forage lands will be established with measured data from a sufficient range and number of locations to calibrate and validate process models for the range of intended applications. The observation network (see Figure 11) will be composed of the existing relevant research studies (including those that are finished and published, including relevant studies from northern US), adding higher quality SOC measurement to existing or planned relevant demonstrations/research sites by applied research organization, AAFC, and/or universities, plus proposed new monitoring/research sites by applied research organization, AAFC, and/or universities to fill gaps with existing sites (see Appendix C).

To adequately cover the range of management, soils, and climates, monitoring sites can include compensated actual farms/ranches when that is the best option to fill knowledge gaps. The management and sharing of the data are an essential aspect of the observation network. The monitoring and data network is well suited built to be built piecemeal to respond to priority knowledge gaps, priority regions, and available funding opportunities. It is desirable to have ongoing measurements to ensure the models are continually validated for changing climate and management refinements over time but it is not necessary to have all locations monitored continually.

There are many reasons for choosing this approach that is mainly based on models. Models can capture many farm-specific influences like weather, soil type, pasture and/or forage vegetation type, amount and timing of grazing land utilization, fertilization, and other amendments, seeding and termination practices etc. Models are versatile and can become a way to translate past, current, and future research investments of management of grazing and forage lands into understanding the impacts of improved management. Practice-based factors are difficult to develop and apply because grazing practices are often difficult to categorize because actual management can be highly adaptive and unique to each farm/ranch because of differences in their grazing resources, herd type (number, breed, producing breeding livestock for sale, backgrounding, etc.) and individual manager preferences. SOC measurement on heterogenous grassland of different types would be so expensive to make them infeasible without high value for increased SOC in today's markets. Modeling can be used to estimate future SOC change whereas measurements are backward-looking with limited ability to make future projections if anything changes from the past.

Finally, this modeling approach is best suited for integration into IMWEBs, other SOC quantification platforms or to other EGS estimators, such as water quality, that are also modeled.

The proposed roadmap is not specific to any process model. In fact, using the mean of outputs of several models may be superior to any single SOC model (Riggers et al. 2019). Further models will improve over time with the continual international investment so the best model now may not to be best for this application in the future. Hence, flexibility in model choice, for models that do require new data that will be difficult to obtain (e.g. detailed soil fractionation for each modeled site), is an attribute of the roadmap.

The types of sites in the observation network will depend on the need for filling identified knowledge gaps testing preferred BMPS, and funding and existing physical opportunities for filling those gaps. Experiments with careful controls are especially useful for validating and calibrating the model. In some cases, a chrono-sequence of farms will be the best way to fill a knowledge gap. Chronosequences are pairs of nearby farms having traditional management and new management of interest (e.g. CGFA identified BMPS) that changed from traditional management at different times since the change. Although not ideal, a chronosequence provides a relatively low cost and rapid method to estimate the effect of the changed management on SOC. Although it will take many years to develop data on the effect of management on SOC, measuring SOC change over time for a single farm can be used to fill an essential knowledge gap if no other option exists.

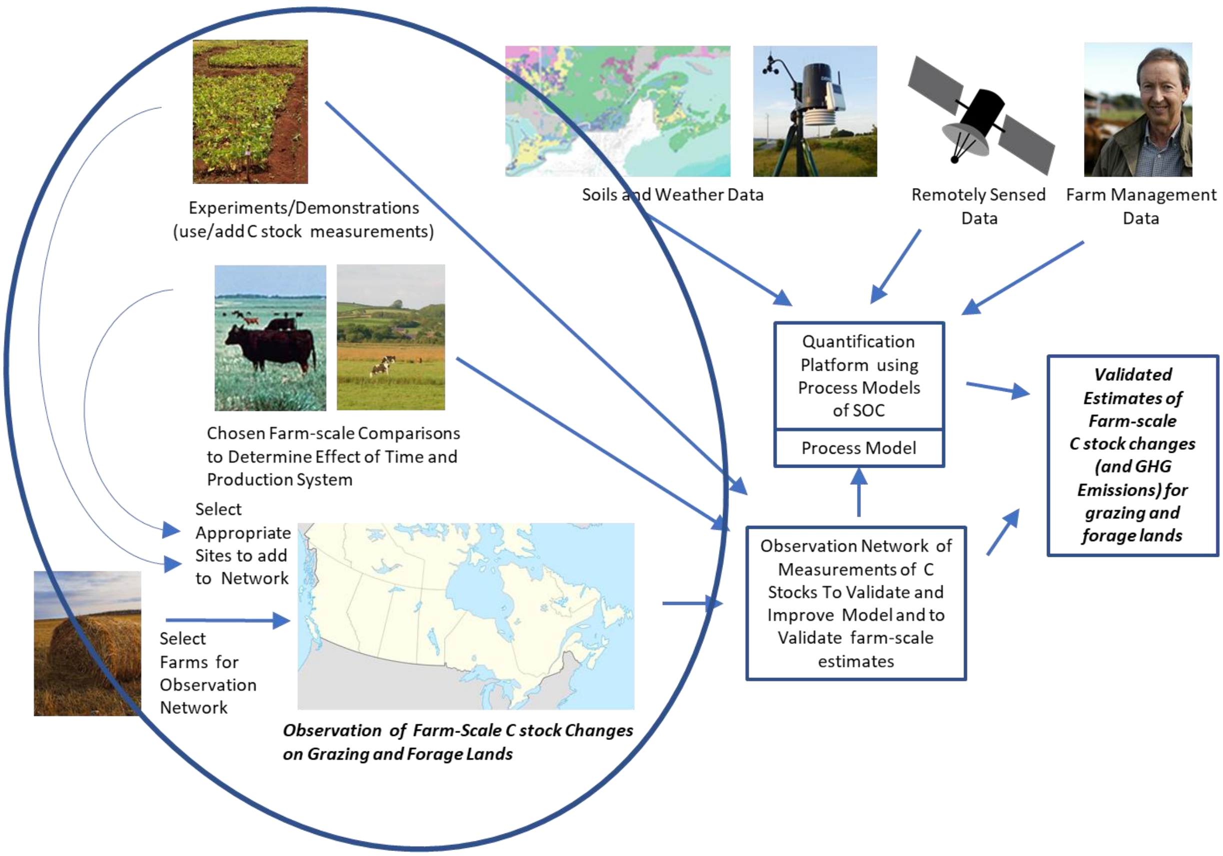

Figure 11: Proposed Observation Network

6.4 Uses of the Canadian Forage and Grassland Observation Network

It is important the Canadian Forage and Grassland Observation Network (CaFGON) meet the needs of various users. One set of users is those that want to use the data in the network to fulfill the Roadmap and thereby estimate SOC stocks and SOC stock change for the current management situation of forages and grassland. Some users are primarily interested in the economic performance of management practices that also increase SOC. Another set of users want to use the data in the network to develop private and public initiatives to increase the adoption of improved management to value the environmental benefits. These users will want information beyond GHG, especially information of impacts of land management on water quantity and quality and on biodiversity. A third set of users want to use the data in the network to improve understanding of mechanisms of how the improved management affects vegetation, soils, and livestock.

This Roadmap focuses on the question of how to best model SOC change: the use of the observations of the SOC stocks and their changes over time to calibrate and validate SOC process models. However, for the observation network to effectively answer that question, it is essential that the observation data contain information on exactly how the land was managed and on the species/cultivars in the vegetation including changes to the relative proportion of the species over time. Management for grazing requires knowing the stocking regime including the sizes, ages, and breeds of livestock. Knowing the productivity of the pasture and/or forage is highly useful to more thoroughly validate and calibrate the models.

An important question is, 'what is the economic performance of the management system?' This is important for several reasons: 1) this will be the question for many contributors of data from demonstrations and applied research so they want access to information relevant to their interests; 2) decision makers for the private or public initiatives to produce SOC increases through adoption of better land management will need to know the economic performance of that management since that determines the attractiveness and feasibility of producers adoption; 3) the data needed for economic performance will also help quantify the GHG impact - specifically livestock performance and yield and quality of pasture and forages are useful to estimate enteric fermentation by ruminants. Hence, we need to consider data on economic performance important to Roadmap purposes and design the data needs and capability of the network appropriately

The desire to use the network beyond soil carbon provides additional rationale for establishing the CaFGON so that it could be expanded to include data needed to support estimates of other ESGs.

Regarding improving understanding of mechanisms, one strength of the accessible observation network is that it enables evaluation across sites so that it is not as necessary to have all aspects to be studied at one site to improve understanding requiring data on those aspects. The observation network does not necessarily have to house all detailed data but should have metadata on what is available and contact information.

6.5 Minimum data sets and number of sites

To meet the above uses, there will need to be a minimum data set of observations or estimates. There will also be recommended data set of observations and/or estimates including recommended ways to observe or estimate data. These dataset requirements in themselves are valuable for those developing new projects with the intent of being connected to the observation network.

To better serve various users of the CaFGON, there could also be an accompanying repository of extension information, reports, papers, posters, conference proceedings, etc. linked to the data in the Network.

The project team estimated that about 50 locations across Canada should be sufficient for a high-quality observation network. Among these locations, some of the 50 locations would have multiple management and some will be completed experiments. Logically the network would be built piecemeal based on the geographical and scope of interest of the funders.

6.6 Roadmap Management

The Roadmap with CaFGON is envisaged as a dispersed system with many partners. The key responsibilities of the roadmap are:

- Overall monitoring, science, and estimating system management
- CaFGON implementation
- Estimation system development and maintenance
- Data collation, sharing, and archiving
- Estimation system implementation

The grassland industry is an essential partner. The industry has a vested interest in quality and use of estimates. They also want to have unfettered access to the estimates so they can use for economic advantage. The Canadian Forage and Grassland Association provides an existing national coordinating body for industry interests.

Canadian science will need to be involved. Agriculture and Agri-food Canada, provincial departments of Agriculture, universities, and applied research groups will be collectively responsible for the observation network. Environment and Climate Change Canada, through their responsibility for reporting carbon stock changes on grassland, is also a logical partner. Within these science partners will come much of the expertise for developing the estimation system including model selection and validation.

For resilience, it is best if the responsibilities for overall system management, data management, and estimation system implementation are shared among many partners so that, if priorities change for one partner, the system can continue without them. Effective data sharing agreements are also required across the partners that enable the system to function efficiently while protecting privacy and intellectual property. Transparency of methods and data will be essential for the various users of the outputs from the system.

Where there are private projects that will gain value from increased SOC over a specified area of grassland, those projects could become a source of new private sector funding to fill needs of the system that are specific to those projects.

It is beyond the scope of this roadmap identification exercise to suggest how the potential partners could meet the collective responsibilities and organization necessary for successful system development and implementation. There does not need to be a one-size-fits-all solution nationally as the particular solutions to that challenge can differ regionally and even by type of production system.

6.7 Summary of the Intended Approach

There is a pressing need to fill gaps in knowledge on the SOC stock change of grazing and forage lands in Canada. A process model-based estimate of SOC that is well validated by independent measurements of SOC change will be most cost-effective and flexible. A well-designed monitoring system that underpins the modeling system enables project developers and producers to capitalize on market opportunities from SOC stock increases. The network will enable new collaboration and assistance for realizing enriched SOC for Canada's agricultural land that would not have occurred otherwise.

7. Potential integration with other EGS quantification

The modeling approach is well suited to IMWEBS. The IMWEBS provides a platform of geospatial data for model input – exactly what is required for modeling SOC. The data needed for the SOC modeling, such as nutrient additions and vegetation management, are also necessary inputs to estimate water quantity and water quality within the IMWEBS environment.

The observation network could provide a collection of sites to add measurements that support the estimation of biodiversity and of water quality and quantity. These measurements are generally costly so are best done on well-chosen sites to represent the range of grassland conditions. Therefore, the observation network can also support the broader application of the IMWEBS platform to other EGS.

8. Recommended Next Steps to Developing an Observation Network

After considering all the responses from the stakeholders and technical advisory group, the project team decided that attempting to develop the full CaFGON from scratch would be too large and complex a task which could struggle to secure funding, governance and consensus between collaborators.

Instead, the project team is proposing to initially develop a smaller data repository platform (DRP) from which to build. The main objective of the DRP will be to collect, manage and share all the past and present datasets available across Canada that have been identified through this project. The data will be hosted in a trusted data management and sharing platform (e.g. Scholars Portal Dataverse, FLUXNET Network) which will be configured to meet the basic requirements of the eventual observation network, and will make the existing datasets available only to collaborators. Datasets will also be linked with models to begin testing the feasibility of the proposed observation network system.

The initial DRP will act as a central node around which collaborators can focus efforts to develop the required governance, agreements, standards, ownership, and long-term funding strategy. The key benefits to collaborators will therefore be data access in a centralized database, and input into the ongoing development towards the fully functional observation network.

Initially, the platform will be open only to collaborators/investors, but the intent will be for the eventual observation network to be open source, potentially with some kind of fee structure to be developed at a later stage.

Once built, the DRP will be extended to include more datasets and monitoring sites as they become available, and to increase functionality as additional uses are identified. The DRP will be used as a proof-of-concept to take to potential long-term funders. Using the learning from the DRP, a detailed strategy for the full observation network will be designed and developed. Collaborators will actively look for funds, grants, private sector investments, voluntary contributions, or financial incentives to develop the full observation network. After securing the funding for the observation network, the experience gathered from the initial DRP will be used to develop the network. High-level next steps are presented in Figure 12 with additional detail below.

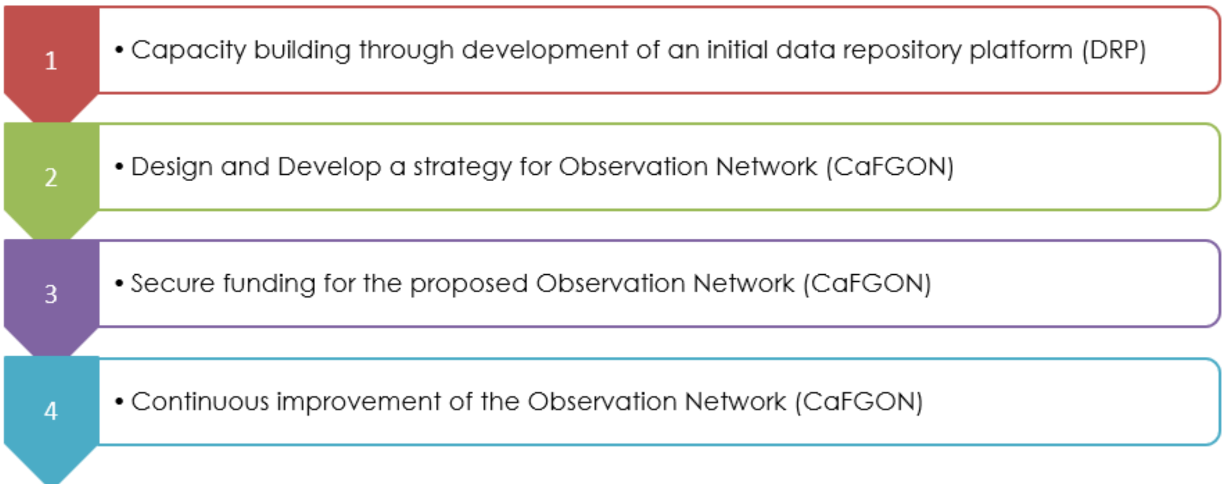

Figure 12: Recommended next steps

Step 1: Capacity building through development of an initial data repository platform (DRP)

It is clear that there are existing observation sites and datasets that are ready to contribute to the network. It will be important to first build a simpler data repository platform (DRP) to host these datasets (see Appendix C) from which to build, rather than attempting to build the network directly. This will enable action to be taken immediately towards building the network whilst proving out the concept to obtain subsequent funding.

Building the initial DRP will instigate discussions on design, governance, data ownership and access policies, observation activities, and ongoing funding, and could avoid some of the foreseen delays regarding these discussions. Categorizing the differing needs and aspirations of potential contributors and immediate users of the database of existing observations will be the essential initial step in this process.

The DRP will be developed by configuring a trusted data management and sharing platform (e.g. Scholars Portal Dataverse, FLUXNET Network) which already exists. Existing resources will be used as much as possible to establish this initial platform and develop a business model.

The DRP development will require funding and other resources. An initial step towards building the DRP would be to develop a short concept note describing the databases and type of platform that would be used, and eventual objective of the observation network (once the platform gains a critical mass of observation sites and data). The concept note could be socialized with various stakeholders and platform developers to be challenged and refined, and to test collaboration potential, ahead of any funding calls.

Various foundations (e.g. Metcalfe, Ivey, Bill and Melinda Gates) have already showed their interest in capacity-building for natural climate solutions such as soil carbon sequestration. The New Digital Research Infrastructure Organisation is a non-profit organization that assists Canadian academic researchers with digital tools and services. They host periodic calls for proposals to develop tools such as the platform being suggested here – their next call is anticipated in 2021.

Step 2: Design and Develop a strategy for the Observation Network (CaFGON)

The design of the observation network should build from the DRP. Data providers will range from government and academic institutions to private companies and land managers. Each of these providers will need to see value in the observation network to participate while being assured that their data will be used appropriately, and access to their intellectual property will be acceptable. The platform should therefore be designed whereby data is available only to other data providers and collaborators (i.e. funders, resource providers, etc.) and any broader distribution will require the explicit consent of data owners.

This step strategy includes identifying knowledge gaps and planning efficient ways to fill those gaps. These gaps can be geographical, types of management, and/or detail (e.g. deeper soil measurement, missing information of vegetation type above- and below-ground growth).

The design of the relevant data sharing agreements and governance structure will be simplified with the development of a small-scale platform, from which the larger observation network can be subsequently built. The experiences and learning from the initial DRP, previous similar projects, and large-scale observation programs will be used to design and develop a broader and more detailed strategy for the full observation network (e.g. business model and funding strategy).

The list of intended uses will be refined and extended based on the experience of initial DRP and user consultation. The Canadian Forage and Grassland Association have already agreed to a secretariat role for managing the initial DRP.

Step 3: Secure funding for the proposed Observation Network (CaFGON)

The goal of this step is to develop the fully functional network with a proper governance and maintenance mechanism and standard data management and sharing policy.

Once the DRP is built alongside collaboration agreements, data sharing agreements, and a governance structure as a proof-of-concept, the concept of extending the DRP to the full observation network can be presented to potential funders for its development and long-term operation. The construction of a network which involves data-sharing and open source data for the purposes of enabling climate mitigation should be able to attract financing, especially with a proof-of-concept. Grants, private sector investments, voluntary contributions, options to utilize funds from carbon taxes, pay-per-play options, and other financial vehicles will be explored to develop and operate the observation network for the longer term.

Step 4: Continuous improvement of the network (CaFGON)

The network will continually work to improve the features and services it can offer according to user requirements, including suitable supporting technologies and BMPs. Identifying and filling knowledge gaps that arise will be an important component of continuous improvement. This will ensure the network continues to add value and maintain income in the longer term. Coordination among the collaborators and investors will be improved. Knowledge and experience will be shared among the stakeholders and new ideas will be generated based on learnings and experiences. Integration of other platforms (example: FLINTpro) will also be explored. The network will support related market and policy instruments to utilize the network, and develop a funding program to support research to fill critical knowledge gaps.

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Appendices

9. Sampling considerations for Direct Empirical Measurement

Sample Representativeness

Having a representative sample to the whole area is essential to the integrity of the estimate of SOC over a whole area based on that sample. Representativeness is accomplished by reducing the opportunity for the sampling to introduce unwanted bias or predictable deviation of the mean of the sample from the mean of the population. Random sampling is the most reliable and practical method to minimize the chance of bias. Randomness means that the sampling is equally likely anywhere. The merits of a specific sampling plan depend on the purpose and scale of SOC quantification, but it still holds true regardless of approach, that the principle of reducing the risk of unwanted bias is essential to quantification.

Stratification

Dividing land into strata is an effective method to optimize sampling resources. Each stratum needs to be delineated so the area covered by each stratum is as similar as practical. If the stratum is homogenous then the expected standard deviation (SD) will be low so fewer samples can be used to estimate the mean value to a given confidence limit than if the stratum is very heterogenous. The strata do not all have to be homogenous. A stratum delineation of areas of heterogeneity can also be useful where it is difficult to subdivide the heterogeneous area into manageable homogenous strata. The sampling resources saved by having lower sampling density in more homogenous strata can be allocated to increase sampling density in more heterogenous strata so all are expected to have similar confidence limits.

There are two aspects of SOC homogeneity that are important for stratification for detecting the change in SOC. One is to be homogenous as feasible in initial SOC content, the other is to be homogenous as feasible in future change in SOC and the factors that drive change, so strata change in SOC is also homogenous over time. Sampling strata is best done randomly to reduce the chance of bias in the sampling; this method is called stratified random sampling.

There is an estimate of SOC for each stratum but not for subareas within each stratum. So, if the stratum has several fields or farms, they all share the same SOC content per unit area. Some form of stratification is necessary to upscale estimates from subarea to the whole area of interest (simplest is to make the whole area one stratum). However, strata can be delineated by any combination of variables that relate to differences in SOC: soil texture, landform, soil erosion or deposition, climate, and weather, estimates of NDVI, drainage, and land use and management history. Land cover from remote sensing will reflect many of these variables so is frequently used as one data layer for stratification. Thus, there are appreciable costs to collect necessary data, collate the data so it is all coherent, and to analyze the data. Point observations of SOC are also extremely useful to validate a stratification approach. Digital soil mapping methods are appropriate to assist in stratification for the initial SOC content. Future changes in SOC are mostly related to changes in future land use and/or management relative to historical land use and/or management. Since both of those changes are likely to correspond to land tenure boundaries, those boundaries are sensible to include in the stratification for SOC change.

The basis for stratification can change over time (especially with land management changes) and so stratification should be performed before each sampling event. Highly efficient stratification, in terms of low spatial density of subarea estimation within homogenous strata, can be developed for a one-time estimation of SOC stocks. However, for SOC change over time, the spatial density of subarea estimation needs to be higher to account for the possibility that each stratum may become less homogenous over time because that affects the validity of the initial spatial density of subarea estimation. Stratum that becomes more homogenous over time may have a higher density of estimation than necessary, but that does not degrade the validity of subarea estimation.

Fixed-depth vs Equivalent Soil Mass and Bulk Density

For valid comparisons of SOC change between baseline and practice change, estimating carbon on a per unit area is essential (as compared to % carbon values). This requires valid estimates of soil bulk density (the weight of soil in a given volume), estimated on a physical soil sample in a qualified lab. Regarding taking a physical soil sample there are generally two main soil sampling/analytical techniques employed: fixed depth (FD) and equivalent soil mass (ESM) in the cores. The FD method expresses the SOC on the basis of sampling depth below the soil surface, whereas the ESM method involves expressing the SOC on the basis of the same soil mass across sampling in the core.

If soil bulk density increases, then the same depth of sampling will include more soil mass. Different practices can affect soil mass, for example, conventional tillage can cause soil volume to increase due to fluffing. No-till or direct seeding can compress soils increasing soil bulk density. Practices that increase the organic carbon content of the soil through carbon sequestration can lead to decreasing bulk density values relative to the mineral content of the soil layer. To overcome these interacting effects, expressing SOC per unit area on the basis of equivalent soil mass can be used. Using this adjustment, the effective depth of sampling is mathematically set so that the increments contain the same mass of soil. The end result is the effect of differences in bulk density of SOC due to natural and management-induced changes in space or time are minimized (Ellert and Bettany 1995; Ellert et al. 2002; Halvorson et al. 2016; Lee et al. 2009; Olson 2013; VandenBygaart and Angers 2006).

Management, geologic, geomorphic, and organic inputs (litter, manure, etc.) are all factors that impact soil bulk density which in turn impacts the SOC values obtained depending on whether the FD or ESM method is used (Ellert & Bettany, 1995; Xiao et al., 2020). For ESM, it is essential to measure soil bulk density each time direct measurements of SOC are performed. Cunningham et al. (2017), determined that to achieve a target precision, it requires about the same number of samples for bulk density as are required for SOC concentration. The lowest uncertainty occurs when the bulk density and SOC concentration are determined from the same soil sample.

Although equivalent soil mass comparisons have become an accepted good practice, there is no agreement on the exact basis. One approach is to use the sampled profile with the least mass as the basis, while another is to use the sampled profile with the most mass, another is to use the average profile mass; each corrects the effect of different mass but each also produces a different value for any comparison (Lee et al. 2009). Regardless of the different approaches, the chosen method needs to be applied consistently in the analysis for meaningful comparisons of SOC change between baseline and project conditions.

Sampling Depth

FAO recommends 0-30 cm for reporting SOC change over periods less than 10 years. However, over longer terms, Knebl et al. (2017) recommend 60 cm deep while Gauder et al. (2016) recommend 90 cm. Current industry consensus and IPCC recommendations are to sample to a 30cm fixed depth as a minimum standard. This is derived from SOC research that has largely focused on cropland soils and the identification of the top 30cm as the active layer. Process models (see below) have therefore largely been developed to model and project SOC changes in the top 0-20 cm – a value for the 0-20 cm layer can be estimated as 2/3 of the value for the 0-30 cm layer measurement in the absence of a more accurate empirical derived relationship. However, the depth of the active layer is likely deeper in grasslands where management is significantly different and deep-rooted perennials are grown. Additionally, our understanding of SOC is evolving to the point that future models and EGS credits may become available for greater depths. Therefore, some practitioners are proposing additional SOC measurements at greater depths for potential future crediting opportunities, and to improve understanding.

However, the relative variability of SOC stock typically increases with depth. Therefore, sampling deeper than where SOC change is occurring reduces the probability of detecting that SOC change or reduces the amount of change if the quantification discounts for the uncertainty of measurement, such as the

Australian Carbon Farming Initiative protocol (Department of Environment and Energy 2018a; b). The draft Climate Action Reserve Soil Enrichment protocol3 is an example where credits are currently awarded for SOC changes in the 30cm layer, but sampling to 100cm with at least two depth increments is recommended in anticipation of future crediting opportunities when models are able to model SOC changes in deeper soil layers.

The soil has genetic horizons and, for many soils, there are large differences in SOC concentration between horizons. However, VandenBygaart et al. (2007) evaluated sampling by genetic horizon for 6 soils across Canada and found for 0-30 cm, sampling by genetic horizons reduced variability for two soils, had little difference for another two, and increased variability for two soils. To 60 cm, fixed depth sampling had lower variability for 5 soils. Vanguelova et al. (2016) also concluded that fixed depth sampling is more efficient and effective (i.e. lower variability) over sampling by genetic horizon.

Bulking soil samples

Bulking or compositing soil samples refers to combining different samples into one to reduce soil processing and analytical effort. The bulked sample provides a better representation of SOC over space since it is made up of many profiles. Poussart et al. (2004) found that bulking 9 cores reduced variance by 10-fold from single cores. The greatest benefit occurred after 4 cores were bulked. However, the bulked sample is for statistical purposes a single sample and provides no information on between sample variability.

The bulked sample produced mass-weighted average SOC concentration. Assuming the carbon input and carbon dynamics over an area are the same, the SOC concentration will increase as the sample mass increases. Consequently, the bulked sample will have a tendency to have a slightly lower SOC concentration than that of a volume-weighted mean; this has been observed (Vanguelova et al. 2016).

For Australia, de Gruijter et al. (2016) concluded that the disadvantages of bulking outweighed the advantages. Chappell and Viscarra Rossel (2013) point out that bulking over a small subarea, as often done for paired sampling, misses variation over the larger field the subarea is located. Nevertheless, they suggest that bulking across a whole stratum within the field can be useful so the bulked samples is across that coarser scale variability.

3 See: https://www.climateactionreserve.org/how/protocols/soil-enrichment/

Paired Sampling for SOC Change

To detect the change, the most effective way is to resample a small area within a field (Chappell and Viscarra Rossel 2013). Various schemes for offset samplings have been used (Ellert et al. 2002; Ellert et al. 2001; McConkey et al. 2020; VandenBygaart 2006; VandenBygaart and Angers 2006; VandenBygaart et al. 2007).

However, the pairing concentrates sampling effort in small subareas so that change over larger areas may not be represented. Spreading the sampling resources over a large area provides more information on variability over the whole area (Chappell and Viscarra Rossel 2013). Thus, to ensure that limited sampling resources are used most effectively, the Australian carbon farming initiative forbids paired sampling (Department of Environment and Energy 2018a; b).

10. Appendix A: ISO 14064 Standard

In cases where good practice guidance from more than one recognized origin exists, the project proponents justify the reason for using the selected recognized origin. Where there is no relevant current good practice guidance from a recognized origin, the project proponents establish, justify and apply criteria and procedures to fulfil the requirements.

The project proponents ensure the GHG project conforms to relevant requirements of the GHG program to which it subscribes (if any), including eligibility or approval criteria, relevant legislation or other requirements. In fulfilling the detailed requirements, the project proponents identify, consider and use relevant current good practice guidance. The project proponents select and apply established criteria and procedures from a recognized origin, if available, as relevant current good practice guidance. In cases where the project proponent uses criteria and procedures from relevant current good practice guidance that derive from a recognized origin, the project proponents justify any departure from those criteria and procedures.

The project proponents select or establish criteria and procedures for identifying and assessing GHG sources, sinks and reservoirs controlled, related to, or affected by the project. Based on selected or established criteria and procedures, the project proponent shall identify GHG sources, sinks and reservoirs as being controlled by the project proponent, related to the GHG project, and affected by the GHG project.

The project proponents select or establish criteria and procedures for identifying and assessing potential baseline scenarios considering the project description, including identified GHG sources, sinks and reservoirs, existing and alternative project types, activities and technologies providing equivalent type and level of activity of products or services to the project, data availability, reliability and limitations, other relevant information concerning present or future conditions, such as legislative, technical, economic, sociocultural, environmental, geographic, site-specific and temporal assumptions or projections.

The project proponents demonstrate equivalence in type and level of activity of products or services provided between the project and the baseline scenario and shall explain, as appropriate, any significant differences between the project and the baseline scenario.

The project proponents select or establish criteria, procedures and/or methodologies for quantifying GHG emissions and/or removals for selected GHG sources, sinks and/or reservoirs.

11. Appendix B: Soil Carbon Protocols Detailed Summary

Climate Action Reserve: Draft Soil Enrichment Projects Protocol

(as of August 7th, 2020 - working group version – not yet available for public comment)

Element	CAR handles it by	Implications
Project Practices	Open-ended (but can't include a land use change, or decrease stocks of woody biomass in the project area), so long as data exists to undergo model validation and calibration for the particular project practices. These include: • Fertilizer (organic or inorganic) application; and/or, • Application of soil amendments (organic or inorganic); and/or, • Water management/irrigation; and/or, • Tillage and/or residue management; and/or, • Crop planting and harvesting (e.g., crop rotations, cover crops); and/or, • Fossil fuel usage; and/or, • Grazing practices and emissions.	Although the suite of practices initially envisioned was quite broad, and the desire was to include 'regenerative ag practices', including incorporating livestock, in practice this is difficult. Soil amendments (e.g. manure or biochar) and inclusion of grazing animals introduces GHG boundary issues when considering baseline and project conditions. This was raised in the WRI Blog regarding whether soil organic carbon could properly be accounted for and the accusation that many of the identified project types are simply 'moving carbon around'.

Additionality	Originally, implementing 1 new practice change over existing practice; Now has a new common practice assessment, and a new CAR SEP Additionality Assessment Tool.	Credits for quantified performance, rather than simple practice adoption - can build on SOC change moving forward but practices need to pass two tests, based on public comments - (1) performance standard test (PST)and (2) legal requirements test. The PST test has two components – a negative list at the county level applying the CAR new additionality tool since some practices are already 50% adopted of total cropland or pastureland area in some counties rendering them ineligible. The second test is Project Specific, where a combination of two or more eligible practices are implemented on a field during the initial year of reporting, notwithstanding any such individual practice being on the negative list. There are time limits listed in this second option for PD's to adopt a new practice. There are allowances in the current draft for projects that rotate improved tillage practices with conventional tillage so as not to be excluded forthright, even if on a negative list for the county, so that climate benefits can be demonstrated/quantified.
Crediting Period	Originally suggested 30 years; over multiple cultivation cycles; but, was revised after public comment period to now have 10-year crediting periods, renewable up to 2 times for a total of 30 years.	Stakeholders felt having a historical baseline for a 30-year crediting period was not sufficient and baselines should be re-assessed every 10 years. PD is still required to report every year; verify up to every 5 years, sample every 5 for true-up and model recalibration. Credits issued upon verification.

Establishing the Baseline	The historical baseline is established for each field for at least one complete rotation of crops and management practices.	From the protocol: The length of the historical period shall be no less than three years, and shall at least be long enough to encompass a complete rotation of crops and management practices, unless a complete rotation extends beyond five years (e.g., if the same crop is grown every year, but the field is only tilled every four years, the historical period must be at least four years). If a baseline rotation extends beyond five years, then the minimum baseline period is five years.

Permanence 100-year Requirement	PD required to monitor, report and replace any reversal for 100 years. Unavoidable reversals – discounts based on risk between 5 to 16.8% Avoidable/Intentional reversals – Project Developer (PD) pays back – legally obligated through Project Implementation Agreement (PIA).	Tonne-Year- partial crediting* (TYA – Tonne Year Accounting). Tonne-Tonne – depends on term of the PIA. If <100 y after crediting; PIA needs to be extended, an alternate mechanism proposed or CAR declare reversal and payback by PD. Although CAR had identified alternate mechanisms in its initial draft, the public comments rejected any kind of flexible mechanisms. So, PD's are required to have a 100-year permanence period for reporting, monitoring and replacing any reversed tonnes. For a 30-year project, this is effectively up to 130 years after the last tonne is credited. Other programs have buffer reserves with discounts based on risk of reversal. A TYA approach with a 20-year PIA looks like this: Crediting for reversible emission reductions will be based on the remaining length of the permanence commitment compared to the vintage year of the credits. For example, if a project executes a PIA with a term of 20 years subsequent to the first reporting period, credits for reversible emission reductions will be issued on the following schedule in Table 0.1 (assuming the permanence commitment is never renewed or extended).

<table>
<tr><td></td><td></td><td>Table 0.1. Schedule for Issuance of Reversible Emission Reduction Credits Under 20-Year PIA
<table>
<tr><th>Project Year</th><th>Percentage of Current Year Emission Reductions for which Credits are to be Issued upon Successful Verification = 1% + Remaining Length of PIA</th></tr>
<tr><td>1</td><td>21%</td></tr>
<tr><td>2</td><td>20%</td></tr>
<tr><td>3 - 20</td><td>19% - 2%[4]</td></tr>
<tr><td>21</td><td>1%</td></tr>
<tr><td>22 - 30</td><td>1%</td></tr>
</table>
</td></tr>
<tr><td>Ownership</td><td>Grower owns GHG rights; transfers ownership to PD contractually; becomes single point of ownership</td><td>Lifts liability from grower to PD; may set stage for civil suits between landowner and lessee.</td></tr>
</table>

4 Each subsequent year after year 3 receives 1% less than the previous year. For example, on year 4 the issuance is 18% of total emission reductions, on year 5 it is 17%, and so on. This reflects that the contractual commitment established after the completion of year one is diminishing over time and, with that, the proportion of emission reductions that can be issued up front.

Quantification	Modeling and Measurement – different levels of hybrid imagined. Model – needs to be validated and parameterized appropriately. 3rd Party Expert Assessment on application of modeling required. Measurement – SOC sampling occurs in baseline year; repeated every 5 years to 'true up' model predictions at a minimum. Other gases -default equations (CAR Grassland CH4 emissions; and IPCC 2019 for N2O/CH4) USDA N2O Hybrid Model (2014)	Must follow CAR Validation, calibration and verification Guide. Peer-reviewed Manuscript can sub in for 3rd party Expert Assessment. Validation dataset will not be available for all geographies/crops – will be limiting. Credits issued based on modeled results, if true-up shows model overpredicted, credits are deducted from issued tonnes. No Guidance on soil stratification (carbon estimation areas), sampling and processing of samples. In most cases, trace gases are either to be modeled or to use default coefficients. Examples in protocol show the 'high level of modeling' vs the 'limited use of models' for specific gases.
Uncertainty Deductions	If Compound uncertainty is > 15% at 95% Confidence Interval (CI), then discounts will apply.	Error from Sampling + Model structural uncertainty = Total.
Guidance on Model True Up and Initialization	The latest CAR document on Model validation, calibration and verification guidance is in development.	The protocol generally treats measurement as a compliance exercise since there is no requirement to strive for any low level of uncertainty with measurements. There may be very high uncertainty for the measured SOC estimates, as high or higher than the model.
Leakage	The latest Protocol introduces mechanisms to account for reduced yields or livestock productivity on project lands.	Discounting for leakage (market shifts or activity shifts) is common practice in protocols. This is a highly subjective process for the reasons why yields may decrease or livestock animals/productivity might decrease (negative leakage). Note that if the reverse is true (increases) not credit is given for positive leakage.

Monitoring and Reporting	Protocol lays out the data points to be monitored and reported – under development.	Requirements are substantial including evidence gathered from the farms; data used to validate model and results, inputs to model runs (over 30 inputs required), crop plans; cultivation cycles and baseline crop rotation data; soil samples and lab analyses, statistical analyses, grazing records (# of animals, grazing records), tillage incidences, land use change records, yield data by farm by crop, fossil fuel consumption for equipment, burning events, by field; and many more. All modeled output to be stored for verifier review.
Verification	Risk based sampling approach/stratified random sampling. Identify ways to leverage proxies to save time and cost. Verifier confirms eligibility, assesses Soil Sampling/testing procedures; assesses independent expert assessment for appropriate use of models; assesses appropriate use of default equations. Samples subset of project data using square root of all fields.	Adopting Alberta's approach to risk-based sampling using mix of tools (NRCS, Extension, OPTis-like tools, FMS software and other data capture systems). If PD can prove model results and input files are not tampered with, then the Verifier will not have to rerun the model to see if they get the same results.

In its purest sense, TYA rewards roughly 1% of credits awarded per year per project for each year it has been protected – based on radiative forcing of 1 tonne of CO_2e. By starting out with a PIA of 20 years, there is some assurance the PD is in it for at least that time frame.

Verra: Draft Improved Agricultural Land Management

(as of August 12th, 2020 - working group version – not yet available for public comment)

Element	Verra handles it by	Implications
Project Practices	Open ended similar to CAR and meant to fit 'regenerative ag practices' (so long as data exists to undergo model validation and calibration for the particular project practices). Net GHGs (CO_2, N_2O and CH_4) are accounted for, similar to CAR SEPP from these practices. Similar to CAR SEPP – no land use change allowed. No cultivating wetlands.	Although the suite of practices initially envisioned was quite broad, and the desire was to include 'regenerative ag practices', including incorporating livestock, in practice this is difficult. Similar to CAR, incorporating livestock and soil amendments (e.g. manure or biochar) and inclusion of grazing animals introduces GHG boundary issues when considering baseline and project conditions.
Additionality	Similar to CAR - the baseline scenario assumes the continuation of pre-project agricultural management practices. Additionality is demonstrated by the adoption, at the project start date, of one or more new practices. Tests include 1. Barriers analysis; 2. Common practice test (cites applicable sources to demonstrate this along with referencing the scale of the data)	Adoption of one or more new practices, cessation of a pre-existing practice, adjustment to a pre-existing practice, or some combination. Any quantitative adjustment (e.g. decrease in fertilizer application rate) must exceed 5% of the pre-existing value to demonstrate eligibility of any practice with a quantitative adjustment. It is likely that a 20% threshold will be applied to a weighted average of the combination of new practices at the state level to demonstrate additionality (still under development). Implications are that if the adoption rate is high for one practice, combining with practices with lower uptake on a weighted average area basis across the group. If have two practices on one farm, can use combined weighted average for penetration rate. The area weighted approach offers more flexibility to implement a combination of practices that are additional.

Crediting Period	Covered in the VCS Standard, for Ag - 20 years; renewable 5 times. Longevity is the monitoring period and it is 30 years.	So, longevity period is the permanence period and will require monitoring for an additional 30 years after the last credit is generated.
Establishing the Baseline	Still remains that the historical baseline be established for each analytical unit (e.g. field) for at least one complete rotation of crops and management practices	For regions where an applicable performance benchmark has been approved by Verra, that benchmark must be applied as the baseline scenario. Otherwise, for each sample unit within the project area (e.g. for each field), practices determined applying a 3-year historic look-back period to produce an annual schedule of activities (i.e. tillage, planting, harvest, and fertilization events) to be repeated over the first baseline period. Baseline emissions/stocks change are then modeled. The baseline scenario is re-evaluated as required by the VCS Standard, and revised, if necessary, to reflect current agricultural commodity production in the region.
Permanence	Outlined in AFOLU Non-Permanence Risk Analysis and Buffer Determination Tool. Longevity period is 30 years after last credit issued (permanence period where monitoring for reversals needs	Applies the approach of establishing a risk rating for reversals and then carving off a certain amount of credits from the Project to deposit in the AFOLU Pooled Buffer Account which is held at the Program level. PD's must apply the Tool and document/justify their self-assessment rating of risk. Verifiers/Validators will assess the appropriateness of the buffer withholding percentage as part of the project process. The risk assessment process is conducted every time the project seeks VCS verification.
Ownership	Refer to VCS Standard v 4.0– Section 3.6.	PD needs to demonstrate they have legal right to control and operate project or program activities. Evidence must be provided such as statue, decree or regulation that demonstrates PD has legal control. For IALM projects, this includes enforceable and irrevocable agreements with landowners in the case of rented or leased land that acknowledge the land lessee or the PD has the right to the arising emission removals/reductions.

Quantification	Combinations of Modeling and Measurement – will depend on emission and removal type and by gas; as well as availability of data for model validation.	Approach 1: Measure and Model – an acceptable model is used to estimate GHG flux based on edaphic characteristics and actual agricultural practices implemented, measured initial SOC stocks, and climatic conditions in sample fields. 5-year measurement true up. Approach 2: Measure and Re-measure –direct measurement is used to quantify changes in SOC stocks. This approach is relevant where models are unavailable or have not yet been validated or parameterized for a particular region, crop, or practice. This approach relies on areas where a performance benchmark exists (the benchmarks are not yet developed and it is expected a PD would establish a performance benchmark baseline approach with Verra – so in effect, Approach 1 is the only approach to start with). Approach 3: Calculation – CO2 flux from fossil fuel combustion and N2O and CH4 fluxes, excluding CH4 flux from methanogenesis, are calculated following 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories using equations contained in this methodology. NOTE: Both programs acknowledge there is little guidance on how to apply the 'Measurement True-Up' to the modeled estimates. This will have to be discovered by those who are trying to apply this very complex process. Measured estimates can have significant variability.
Uncertainty Deductions	If Compound uncertainty is > 15% at 95% Confidence Interval (CI), then discounts will apply.	Error from Sampling + Model structural uncertainty = Total. Won't truly know this until the methodology is trialed.

Guidance on Model True Up and Initialization	Pending.	Verra has not developed any guidance on this 'true up' approach with measurements.
Leakage	Methodology assumes no leakage.	Inclusion of organic amendments (manure, biochar, compost) and allowing grazing animals into the project w/o consideration of baseline conditions and the GHG boundary is a leakage concern that may have been missed (activity shifting to the project w/o considering the GHGs or SOC in the baseline).
Monitoring and Reporting	Protocol lays out the data points to be monitored and reported –under development.	Monitoring procedures included in both the VCS standard 4 and the methodology. Choice of quantification method will also determine the evidence and data to be monitored.
Verification	Methodology lays out areas that need monitoring and verification. Very little guidance specific to the meth wrt verification.	Section 4 of VCS Standard v4 and Methodology. Occurs at least one every 5 years; can occur sooner but when the PD wants to have credits issued is the trigger – same as CAR. Under development.

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12. Appendix C: List of existing SOC databases and monitoring sites in Canada

SN	Province	Site	Operator	Contact	Management
1	AB	Lacombe Research Station	AAFC	Dr. Vern Baron	Information not yet available
2	AB	Mackenzie Applied Research Association	ARECA	Samuel Peprah	Information not yet available
3	AB	Beaver Lodge - transition zone	AAFC	Bharat Shrestha	Information not yet available
4	AB	Stavely/Lethbridge	AAFC (Furnace plots)	Willms/Hao/Bork	Land Use Systems
5	AB	Benchmarking study (>100 sites)	U of A	Bork	Grazing (+/-)
6	AB	Land use comparisons (7-15)	U of A	Bork	Land use type
7	AB	Mixedgrass C assessment (9 locations)	U of A/AAFC	Laforge/Bork	Stocking rate
8	AB	Various local studies/experiments	U of A	Carlyle/Bork/Cahill/Chang	Drought, warming, precip, stocking, land use, agroforestry, etc.
9	AB	ARECA Sites/Forage Associations?	ARECA	Devon Lloyd	Advanced pasture management systems
10	AB	Agro-forestry data by University of Alberta	U of A	Scott Chang	Agro-forestry impacts on C storage

11	AB	Smoliac site/Mixed mesic site	AAFC	Mike Alexander (AEP)	Information not yet available
12	AB	Seacrest site	AAFC	Ben Ellert	Annual crops with crested weed grass rotation
13	AB	Onefour site	AAFC	Benjamin Ellert	Forage productivity dataset 1939
14	AB	Fluxnet site	AAFC	Benjamin Ellert	grassland site with details
15	AB	Larry Flanigan Flux net site	AAFC	Benjamin Ellert	Information not yet available
16	AB	CFB Suffiled	AAFC	Benjamin Ellert	Information not yet available
17	AB	CFB Wainwright	AAFC	Benjamin Ellert	Information not yet available
18	AB	Breton Plots - 1930	AAFC	Dick Purbeen	Forage rotations
19	AB	Bow Island site	AAFC	Benjamin Ellert	Information not yet available
20	AB	Lethbridge, AB	AAFC	Benjamin Ellert	Environmental science
21	AB	Lethbridge, AB	AAFC	Monika Gorzelak	Soil fertility and nutrient management
22	AB	Lethbridge, AB	AAFC	Xiying Hao	Soil science-chemistry
23	AB	Lethbridge, AB	AAFC	Roland Kroebel	Modeling/simulation/forecasting; HOLOS
24	AB	Lethbridge, AB	AAFC	Francis (Frank) Larney	Soil science-land use and evaluation
25	AB	Lacombe, AB	AAFC	Vern Baron	Agronomy-cropping systems
26	AB	Lethbridge, AB	AAFC	Charles Geddes	Agronomy-weed biology, ecology and management
27	AB	Lethbridge, AB	AAFC	Jonathan Neilson	Potato health
28	AB	Lethbridge, AB	AAFC	Karen Beauchemin	Ruminant nutrition
29	AB	Lethbridge, AB	AAFC	Tim McAllister	Rumen microbiology
30	AB	Lethbridge, AB	AAFC	Stacy Singer	Forage biotechnology

31	AB, SK, MB	AMP grazing study (60 ranches)	U of A	Boyce	Grazing mgmt. & historical land use
32	BC	BCFC Demo Site 1	BCFC	Serena Black	Rotational Grazing/No-Till Annual Forage Establishment
33	BC	BCFC Demo Site 2	BCFC	Serena Black	Rotational Grazing/No-Till Annual Forage Establishment
34	BC	BCFC Demo Site 3	BCFC	Serena Black	Rotational Grazing/No-Till Annual Forage Establishment
35	BC	BCFC Demo Site 4	BCFC	Serena Black	No-Till Perennial Forage Establishment
36	BC	BCFC Demo Site 5	BCFC	Serena Black	No-Till Annual Forage Establishment
37	BC	BCFC Demo Site 6	BCFC	Serena Black	No-Till Annual Forage Establishment
38	BC	BCFC Demo Site 7	BCFC	Serena Black	No-Till Annual & Perennial Forage Establishment, Creep Grazing
39	BC	BCFC Demo Site 8	BCFC	Serena Black	No-Till Annual & Perennial Forage Establishment
40	BC	BCFC Demo Site 9	BCFC	Serena Black	No-Till Annual & Perennial Forage Establishment, Cover Cropping
41	BC	BCFC Demo Site 10	BCFC	Serena Black	No-Till Annual & Perennial Forage Establishment
42	BC	BCFC Demo Site 11	BCFC	Serena Black	No-Till Annual & Perennial Forage Establishment
43	BC	BCFC Demo Site 12	BCFC	Serena Black	No-Till Perennial Forage Establishment
44	BC	BCFC Demo Site 13	BCFC	Serena Black	No-Till Perennial Forage Establishment

45	BC	Peace River Forage Association of BC	Talon Gauthier	Talon Gauthier	Annual-Perennial Cropping System Integration
46	BC	Summerland, BC	AAFC	Tom Forge	Applied soil ecology / nematology
47	BC	Summerland, BC	AAFC	Kirsten Hannam	Climate impact – water and nutrient management
48	BC	Summerland, BC	AAFC	Mehdi Sharifi	Soil and nutrient management
49	BC	Agassiz, BC	AAFC	Shabtai Bittman	Agronomy, sustainable cropping systems
50	MB	Manitoba Beef & Forage Initiatives	MBFI	Mary Jane Orr	Rotational Grazing
51	MB	Manitoba Beef & Forage Initiatives	MBFI	Mary Jane Orr	Set Stock Grazing
52	MB	Manitoba Beef & Forage Initiatives	MBFI	Mary Jane Orr	Degraded soil rejuvenation
53	MB	MFGA AGGP Site 1	Brandon University	Terence McGonigle	Intensive rotational grazing, increase sward legume content
54	MB	MFGA AGGP Site 2	Brandon University	Terence McGonigle	Annual-perennial cropping systems integration, 4R Nutrient management
55	MB	MFGA AGGP Site 3	Brandon University	Terence McGonigle	Annual-perennial cropping system integration, increase sward legume content
56	MB	MFGA AGGP Site 4	Brandon University	Terence McGonigle	Intensive rotational grazing, annual-perennial cropping system integration, bale grazing

57	MB	MFGA AGGP Site 5	Brandon University	Terence McGonigle	Intensive rotational grazing, annual-perennial cropping system integration, bale grazing, increased legume content
58	MB	MFGA AGGP Site 6	Brandon University	Terence McGonigle	Intensive rotational grazing versus continuous grazing split-plot
59	MB	MB FYBA Site 1	MB Ag	David Whetter	Landscape use optimization
60	MB	Glenly long term research site	University of Manitoba	Dr. Martin Entz	Annual-Perennial Cropping System Integration
61	MB	Brandon, MB	AAFC	Aaron Glenn	Agro-micrometeorology
62	MB	Brandon, MB	AAFC	Taras Lychuk	Agronomy, integrated crop production systems
63	MB	Brandon, MB	AAFC	Henry Wilson	Hydrology and biogeochemistry
64	NB	Tantramar Community Pasture	NBSCIA	Matt Beal	Rotational grazing
65	NB	NBSCIA Forage Cultivar Evaluations	NBDAA	Ray Charmichael	4R Nutrient Management
66	NB	Local Valley Beef	LVB	Louis-Pierre Comeau	Rotational Grazing
67	NB	Fredericton, NB	AAFC	Louis-Pierre Comeau	Landscape and soil carbon
68	NB	Fredericton, NB	AAFC	Claudia Goyer	Molecular bacteriology
69	NS	Cape John Community Pasture	Cape John Community Pasture Committee	Jonathan Wort	Rotational grazing
70	NS	Dalhousie University - University Campus	DAL	Derek Lynch	Grazing system enhancement

71	NS	Dalhousie University - University Campus	DAL	David Burton	Soil Carbon Dynamics
72	NS	Nappan Research Station	AAFC	Yousef Papadopolous	Enhanced grazing sward development
73	NS	Nappan Research Station	AAFC	John Duynisveld	Rotational grazing
74	ON	20 Ranch Grazing sites	University of Guelph	Kim Schnider and Ralph Martin	Silvopasture system
75	ON	Elora Research Station	University of Guelph	Ralph Martin	Annual-perennial cropping system integration
76	ON	Elora Research Station	University of Guelph	Kim Schnider and Ralph Martin	Enhance pasture system performance and soil carbon sequestration
77	ON	FERCA	Bas-St-Laurent	CDPQ	Pasture Dairy Systems
78	ON	Ottawa, ON	AAFC	Liang Chang	Agricultural scientist, Agri-environment Division
79	ON	Ottawa, ON	AAFC	Ed Gregorich	Soil science
80	ON	Ottawa, ON	AAFC	Ward Smith	Physical scientist, Agri-environment Division
81	ON	Ottawa, ON	AAFC	Albert VandenBygaart	Soil Science
82	ON	Ottawa, ON	AAFC	Andrew VanderZaag	Air and water quality
83	ON	Ottawa, ON	AAFC	Devon Worth	Research Technician, Living Laboratories Division
84	ON	Guelph, ON	AAFC	Pamela Joosse	Soil and nutrient management (Knowledge Technology Transfer)
85	ON	Harrow, ON	AAFC	Craig Drury	Soil biochemistry and soil management

86	ON	Harrow, ON	AAFC	Jingyi Yang	Soil science and modelling
87	PEI	Charlottetown, PEI	AAFC	Judith Nyiraneza	Nutrient management
88	QC	UQAT	UQAT	Vincent Poirier	Information not yet available
89	QC	McGill	McGill	Phillipe Séguin	Information not yet available
90	QC	Cooticook	Cooticook	Nicos Keable-Vézina	Information not yet available
91	QC	CEROM	CEROM	Francis girard	Information not yet available
92	QC	CETAB	CETAB	Jean Duval	Information not yet available
93	QC	Université Laval	Université Laval	Caroline Halde	Information not yet available
94	QC	AAFC Ste-Foy	AAFC Ste-Foy	Gaetan tremblay	Information not yet available
95	QC	AAFC Ste-Foy	AAFC Ste-Foy	Martin Chantigny/Emilie	1642 -Corn based silage vs forage.
96	QC	Agrinova	Agrinova	François Tremblay	Information not yet available
97	QC	CDPQ	CDPQ	Céline Georlette	Information not yet available
98	QC	Quebec, QC	AAFC	Denis Angers	Soil management and conservation
99	QC	Quebec, QC	AAFC	Martin Chantigny	Soil biochemistry and nutrients
100	QC	Quebec, QC	AAFC	David Pelster	GES and exchange soil-atmosphere
101	QC	Quebec, QC	AAFC	Marie-Noelle Thivierge	Forage plant ecophysiology and agronomy
102	QC	Sherbrooke, QC	AAFC	Nicolas Devillers	Pork behaviour and welfare
103	QC	Sherbrooke, QC	AAFC	Rajinikanth Rajagopal	Management and treatment of effluents
104	SK	LFCE	U os S	Jeff Schaenau	Soil and Manure interactions
105	SK	LFCE	U os S	Bart Lardner	Grazing and forage management systems
106	SK	AAFC Swift Current – Research Site 1 (2000-2020)	AAFC-Swift Current Research and Development Centre	Drs. Alan Iwaasa and Aklilu Alemu	Continuous and Rotational Grazing, with non-grazing enclosures.

107	SK	AAFC Swift Current – Research Site 2 (2006-2020)	AAFC-Swift Current Research and Development Centre	Drs. Alan Iwaasa and Aklilu Alemu	Continuous and haying.
108	SK	Pasture #1 – seeded to mixture of native grasses and legumes (12 species vs 7 species).	AAFC	Aklilu Alemu	Information not yet available
109	SK	Pasture #2 – seeded to a binary mixture of native and tame grasses and legumes.	AAFC	Aklilu Alemu	Information not yet available
110	SK	Pasture #3 – seeded to meadow bromegrass.	AAFC	Aklilu Alemu	Information not yet available
111	SK	SK pastures - Govenlock, Nashlyn and Battle Creek pastures in southwest Saskatchewan	ECCC	Robin Bloom	Advanced dryland pasture management systems
112	SK	Saskatoon, SK	AAFC	Haben Asgedom Tedla	Systems Agro-Ecology
113	SK	Saskatoon, SK	AAFC	Darrel Cerkowniak	Data analysis, Agri-environment Division
114	SK	Saskatoon, SK	AAFC	Reynald Lemke	Soil Science, agronomy

115	SK	Saskatoon, SK	AAFC	Raju Soolanayakanahally	Plant physiology, agroforestry
116	SK	Saskatoon, SK	AAFC	Jennifer Town	Soil microbiology
117	SK	Saskatoon, SK	AAFC	Edmund Mupondwa	Technoeconomic analysis, bioeconomy
118	SK	Swift Current, SK	AAFC	Luke Bainard	Soil microbiology
119	SK	Swift Current, SK	AAFC	Mervin St. Luce	Field agronomy (cereals and pulses)
120	SK	Swift Current, SK	AAFC	Aklilu Alemu	Ruminant nutrition
121	SK	Swift Current, SK	AAFC	Jillian Bainard	Range and forage plant physiology
122	SK	Swift Current, SK	AAFC	Alan Iwaasa	Grazing management
123	SK	Indian Head, SK	AAFC	Shathi Akhter	Agroecosystems
124	SK	Indian Head, SK	AAFC	William May	Crop management agronomy

13. Appendix D: Technical Advisory Group (TAG)

Name	Affiliations
Alan Iwaasa	Research scientist - Grazing Management at Agriculture and Agri-Food Canada
Bharat Shrestha	Biology Study Lead, Soil Health and Fertility Development at Agriculture and Agri-Food Canada
Brian Eaton	Manager, Environmental Impacts, InnoTech Alberta
Brian McConkey	Chief Scientist, Viresco Solutions Inc.
Cameron Carlyle	Professor, Agricultural Life amp Environmental Sciences department, University of Alberta
Cedric MacLeod	Executive Director, Canadian Forage and Grassland Association
Claudia Wagner-Riddle	Professor of Agrometeorology, School of Environmental Sciences, University of Guelph
Devon Worth	Technician, Agriculture and Agri-Food Canada
Edward Bork	Professor, Faculty of Agricultural, Life and Environmental Sci - Ag, Food & Nutri Sci Dept, University of Alberta
Glenn Friesen	Industry Development Specialist, Manitoba Agriculture
Kim Schneider	Assistant Professor, Department of Land Resource Science, University of Guelph
Lauchlan Fraser	Professor, Department of Natural Resource Science, Thompson Rivers University
Majid Iravani	Applied Research Scientist at Alberta Biodiversity Monitoring Institute (ABMI)
Marian Weber	Lead, EcoServices Network
Marie-Élise Samson	Ph. D. Candidate in soil conservation, Laval University
Matthew Wiens	Land management specialist, Manitoba Agriculture
Maxime Leduc	Postdoctoral Fellow, Université du Québec à Montréal
Pascal Badiou	Lead DUC Researcher, Institute for Wetland & Waterfowl Research
Roland Kroebel	Research scientist - Grazing Management, Agriculture and Agri-Food Canada
Sarah Pogue	Post-Doctoral Fellow, Agriculture and Agri-Food Canada.

Serena Black	Science Research Specialist, Industrial Forestry Service
William Salas	President and Chief Scientist, Applied GeoSolutions

14. Appendix E: Summary of the project activities

Project Inception activities

The project started with a kick-off meeting clarifying the scope of work, overarching questions, and project work plan. In this stage, the project team undertook a literature review including emerging initiatives on SOC modelling and measures approaches and identification of the gaps in knowledge and data. Based on the data gaps and existing resources, the project team proposed four roadmap options. The project decided to organize two TAG (see Appendix D) meetings and one stakeholder workshop. Participants of these events were selected for their level of knowledge and expertise.

1st Technical Advisory Group (TAG) Meeting

On August 18, 2020, Viresco Solutions Inc. hosted the 1st Technical Advisory Group meeting for developing the SOC Quantification Roadmap for Grasslands and Pastures. In total 19 participants attended the event. The CAP-funded Ecoservices Network project – Integrated Modeling to Assess the Ecosystem Service Benefits of Agricultural Beneficial Management Practices was presented in the event. The draft report was shared ahead of the meeting and summarized during the workshop. The four possible roadmap options for developing the SOC Quantification approaches for Grasslands and Pastures were presented.

High-level insights of the questions, comments and feedback session included:

- Consider farmers’ and producers' perspectives (needs and requirements) in the project.
- Consider payments/rewards to the farmers and producers for providing datasets (increases the cost of the network).
- The proposed model should not be complicated for the farmers and producers (end users). It should be a user-friendly platform for them.
- Develop proper governance and management of the network with a funding mechanism and specific roles and responsibilities.
- Consider getting good quality geospatial layer of land cover/grasslands in this initiative.
- Develop a list of attributes/datasets and how they will be collected. This should be discussed with researchers, scientists, subject matter experts, industry associations, end-users (farmers and producers), project developers, stakeholders from government and private sectors.
- Some feedback that estimates of SOC from a process model that is well validated by independent measurements of C change will be most cost-effective.

- The hybrid method of quantification by modelling and measurement will be dynamic and will allow refinement of models as per the measurement data that address different uncertainties at spatial and temporal scale.
- Collecting and managing data for the 50+ sites across Canada will be challenging due to cost and related issues.
- The Roadmap needs to outline/acknowledge where specific provincial gaps (e.g. baseline data availability) exist, as well as provincial partners/resources. It also needs to outline/evaluate where there currently isn't enough data to proceed with various methods for modelling, etc.
- The roadmap should develop a mixed solution that would enable government, academic and industry associations (e.g. forage producer associations) to partner on the implementation. Producer associations would be excellent at providing observation support providing there are resources to support them; but developing a program that could be housed under existing networks/associations would reduce confusion for producers while building local/regional/provincial capacities.
- Challenges in maintaining or continuing the initial study for a longer period of time and the cost associated with sufficiently high enough spatial and temporal resolution of sampling.

Stakeholder workshop

On September 10, 2020, Viresco Solutions hosted the stakeholder meeting to collect comments and feedback from a broader group on the recommended roadmap strategy for the SOC change quantification for Grasslands and Pastures. In total 51 participants covering a broad range of faculties (e.g. academia, Provincial and Federal government, researchers, scientists, industry associations and private sector) attended the workshop. The CAP-funded Ecoservices Network project – Integrated Modeling to Assess the Ecosystem Service Benefits of Agricultural Beneficial Management Practices was presented in the event. The draft report was shared ahead of the meeting and summarized during the workshop. The four possible roadmap options for developing the SOC Quantification approaches for Grasslands and Pastures were presented. Feedback from participants was gleaned through two interactive sessions in which participants were asked to discuss feedback on:

1. The general approach of models linked with an observation network, including sub-topics on governance, funding and gaps and intended uses, and,
2. Detailed input on specific aspects:
    a. Observation Network: Sampling Design and Methodology
    b. Sites and Datasets: Existing and potential observation sites and datasets that could be used

c. Beneficial Management Practices: which BMPs should be prioritised for inclusion and why; what are the gaps?

Based on feedback from the participants the recommended approach of modeling supported by direct measurement from an observation network was selected as the intended approach. The team sought clarification on some feedback and comments after the workshop with individuals.

A summary of the breakout sessions is given below:

Governance and maintenance:

- It was suggested that Agriculture and Agri-Food Canada (AAFC), Environment and Climate Change Canada (ECCC), or Natural Resources Canada (NRC) could take the leadership role in governing and maintaining the proposed soil observation network individually or collaborating with each other. Various associations (e.g. CFGA, SSCA), groups, and industries could support/manage this network (so-called 'Secretariat). The USDA supports and maintains these types of datasets in the USA.
- Leadership from the industry could also be considered but some participants doubted that the private sector would be interested in financing the network as they may not see direct benefits. The network roles could be distributed regionally to account for different regional opportunities and contexts with national coordination.
- Experience from previous similar projects and large-scale monitoring programs could be considered to develop the governance and maintenance mechanism. The Living labs division with AAFC is currently working on a database/portal to store data by both AAFC and non-government users. It may be useful to discuss the proposed network with them and learn from their experiences.
- Organic Agriculture Centre of Canada of Dalhousie University could provide an example template for the governance structure of a national initiative that involved governments, industry, and researchers.
- The datasets could be open access from a central portal. The business model could be chalked out for various investors and then governance structure could be developed for running a longer-term financially sustainable network.

Funding:

- Funding for this proposed network could be managed from the Canadian Agricultural Partnership (CAP), AAFC A-Based funding, AG-based initiative of ECCC, etc. Industry groups and NGOs need to start talking with their provincial government reps on CAP teams about the need for funding of this network now as new CAP program discussions have already started.

- Long term research funding (federal and provincial) could be explored through NSERC or AAFC. A German model of research funding for collecting long term comprehensive management datasets was suggested.
- The private sector, big industries, industry partners (e.g. BCRC, BFO, Beef science cluster funding, Beef Farmers of various provinces, AAFC Cluster Projects- Beef/Dairy), Soil Health Institute as well as foundations (e.g. Metcalfe, Ivey, Bill and Melinda Gates) and associated organizations could be also considered.
- Collaboration among academia, NGOs/ENGOs, industries, and the government will be required to develop the proposed network. This network could also partner with the NSERC alliance, linking with Soil Health Institute or Regeneration Canada.
- Regulated market opportunities would stimulate the need for monitoring and investment in a national soil observation network.
- The network could partner with national ENGOs already working with land managers across the country and in various provinces (e.g. DUC, NCC, MHCC, etc.) and leverage their networks. For example, funding for the network could come through programs like NAWMP/NAWCA or various foundations like Metcalfe, Ivey, Bill and Melinda Gates, etc.
- Banks could be approached to share the idea and talk about funding. Banks wanted EFP (Exchange of Futures for Physical) to demonstrate reduced risk which can be done in the proposed network. If they see that higher SOC can reduce risks in the long term, they might be interested in this project.
- A portion from Carbon taxes could be combined with forages and beef production checkoffs and funding to invest in this network. Funds generated from large emitters could be used to help build the offsets through this network and generated carbon credits could be used by them.
- A clear concept of the proposed network could be developed, and technology could be used to decrease the cost of sample collection in the network.
- Comments that long-term continuity of the network and cost associated with the sufficiently high spatial and temporal resolution of sampling will be a significant challenge for the network.

Gaps and Intended uses:

- Participants mentioned that there is a massive gap in terms of historical datasets, consistent and reliable measurement datasets, no centralized platform for accessing data, and no effective means of capturing these datasets in a central platform.
- Models can have capability limitations regarding the capture of management changes, due to a lack of suitable datasets. Datasets generated through this network will be useful for various purposes like model calibration, validation, and evaluation.

- The main research priorities should be identified based on what we have and what we don't have. Then relevant datasets should be collected through this network. Participants shared their needs and requirements about various types of datasets.
- There might be some producers who will be interested to support this and provide access and track the collected datasets. Maybe the network needs to consider payments to the producers for collecting and sharing the data. Short term values can be generated for producers to interest them. Better tracking mechanisms should be established for the required datasets.
- This network should be considered as a start-up project for the ongoing provision of information, rather than a one-off research project. It is not clear how NIR reporting can be harmonized with this initiative. The network datasets can be used in NIR to defend to the UNFCCC.

Observation Network:

- Participants recommended various important areas to shape the principles and measurement approaches for the proposed observation network.
- Participants shared their opinions about the soil sampling depth ranging from 30 cm to 1m, but noted sample depth also depends on the type of sites and required datasets.
- Participants felt that the network should have a standardized method/system of collecting data that could be integrated with the soil observation network properly and ensure good quality data collection in the long run. This standardized method/system could be linked with NGOs seeking to develop carbon programs and already working with producers (such as the Ducks Unlimited Canada revolving land purchase program).
- Initially, the project should start with identifying and collecting available data (above- and below-ground, management) and set up and run an initial model to help identify the existing gaps in data and limitations of the models for simulation of management practices. Then the network should try to get access to the existing data (mostly carbon) which can be very challenging.
- The network needs to explore if it can use spatio-temporal proxies from remote sensing as input data to feed input parameters in any process-based model. Translation between the RS proxies and the required data for input parameters is not really straightforward. Also, there are several monitoring sites across Alberta with biodiversity and land cover/HF data that could be part of the new observation network. The process-based carbon models consider different carbon pools that can be calibrated if appropriate measurements are available.
- Currently, no carbon or soil model can consider vegetation composition change and its effect on soil physio-chemical and biological processes; water/hydrology models, biodiversity models, and geochemical models all are setup separately and they don't really talk to each other.

Sites and Datasets:

- Participants mentioned the past and present research sites and datasets they have managed, or they are aware of. (See Appendix C)
- Collecting and managing datasets for the 50+ sites across Canada will be challenging.
- The network needs to decide how the data will be collected (methodology, standardized system), at what cost, from whom, and how the network can work with the existing sites. An active entity (e.g. CFGA) needs to manage the network data repository effectively and efficiently establishing a secretariat for the network. The network also needs to make sure that these data will be used for the public good.
- Producers might be interested in collecting and sharing the data for the network for a certain cost which the network has to convince or negotiate. The producer also needs to understand the benefits and value of the proposed network.

BMP management areas:

- Six focal BMP management areas were presented to the participants and comments were taken to identify the priority management areas and how they can be used to align with their potential intended uses.
- Participants requested to consider some specific management areas based on their experiences and requirements like - enhanced tannin cultivars and other plant traits that can provide additional GHG reduction benefits, maintained productive plant species mix by aggressively managing invasive plants, water provision to cattle could be a BMP under riparian areas, the riparian zone could be extended to the flooding zone, water quality for livestock could be another BMP for the riparian area management area, Legumes contribution to C in bio-diverse systems.
- The proposed network needs to know how to deploy individual BMPs in a systems-based approach to optimize production and to optimize C sequestration.

2nd Technical Advisory Group (TAG) Meeting

On October 6, 2020, Viresco Solutions Inc. hosted the 2nd Technical Advisory Group meeting for finalizing the recommendations of the SOC Change Quantification Roadmap for Grasslands and Pastures. In total 20 participants attended the event. The project updates and feedback to date were presented in the beginning of the event. Dr. Brian McConkey recapped the main points of the recommended approach “modeling with observation support” and soil observation network. A summary of the recommendations received and proposed next steps were shared for feedback from the TAG: beginning with an initial data repository platform and build toward forming the broader Observation Network at the national level. Cedric MacLeod shared the list of observation sites collected so far and requested any additional sites and datasets to add. Dr. Marian Weber thanked all the members of the Technical Advisory Group for their active participation and valuable contribution and creating the momentum towards the much-needed.

High-level insights of the questions, comments and feedback session of the meeting are mentioned below:

1. The momentum for developing the Observation network created through the project will be continued even after the completion of the project. CFGA with support from Viresco will actively look for funding to implement the recommended steps.
2. The project needs to discuss the minimum and preferred datasets/number of variables required for a practical and reliable model/assessment/observation and work for developing these. Some of the datasets collected at UofA by Edward Bork and Cam Carlyle can be considered for developing the minimum datasets/number of variables required for the Soil Observation Network. These minimum and preferred datasets will give us an idea about the budget, process, and engagement of various stakeholders.
3. An incremental approach will keep the network agile and be more attractive to investors who seek smaller, more concise projects. Incremental construction should focus limited resources on pieces that will generate the most value or are in the highest demand.
4. A suitable name for the observation network is going to be important to decide early/now. The name should incorporate the idea that this can go beyond soils and soil carbon. [Canadian Forage and Grassland Observation Network (CaFGON) – Guiding the way to profitable natural climate solutions has been subsequently suggested as a name-tagline for the observation network].
5. How does the size of datasets used for the conservation cropping protocol compare to the datasets required for grasslands given the significant increase in variability and uncertainty? For no-till/reduced till offsets and methodology used in NIR, dataset requirements are quite small. Maybe a dozen long-term sites with high-quality datasets were used for them and compared against the sense of baseline. For example, conservation cropping protocol compares against the baseline of conventional tillage systems. Maybe the process is different for the grazing system as it is really difficult to get a rigorous comparison. Around 50 high-quality sites might be sufficient for the network where a number of those will be research sites with comparisons. If individual time series data are not available, more than 50 actual physical sites may be required. Models don’t work on perennial crop systems as they are hard to calibrate. This a challenge. So, priorities need to be finalized to do this work with limited resources.
6. Prioritization of resources to answer priority questions is key: could be BMPs, locations, grassland types, etc. Time series data is rare, but there is potential to use retrospective data.

7. The project is aiming to develop the platform hosting all the existing datasets. There are several platforms that already exist like Scholars Portal Dataverse that could perform the function of the initial data repository and data sharing. There is a big push from the funders to share the datasets. With limited funds, it will be more productive to gather data and make the data usable rather than working on the software.
8. The focus should be on adapting/configuring existing software/platforms/frameworks for this purpose, not developing from scratch. It will be important to communicate the overall goal (mitigating climate change from smarter data management and sharing, and improved soil management) to the platform developers. The project needs to find ways to stimulate collaboration among partners and reward the collaborators for sharing datasets. The 2-page concept note will be a great idea to collect feedback from the interested partners/collaborators and trust can be brought among them by considering their opinions. Then the concept note can be used to apply for funds (e.g. the New Digital Research Infrastructure Organization).
9. There is an urgent need for sharing the data at some point. But regarding data sharing, researchers will be very wary of sharing data until they have peer-reviewed published papers – there will be a lag between generated datasets and matured datasets. However, researchers should also understand the importance of sharing these datasets because of the expense of creating them.
10. An article about data sharing (i.e. Online Machine Learning for Collaborative Biophysical Modelling) could be a useful guide. The proposed method uses data held by multiple parties without sharing it.
11. The agreement that starting with restricted data access moving towards the goal of open access is appropriate. Scholars Portal Dataverse shares password protected datasets when requested. They try to be supportive to collaborators in terms of accessing the datasets. FLUXNET Network (eddy covariance measurements of carbon dioxide and water vapor exchange) can serve as a model for the soil observation network.
12. The initial data repository should configure existing software and datasets to our needs, rather than build from scratch. Everybody needs to understand the common goal of the project which will help us to overcome the challenges regarding datasets sharing.
13. Learnings from the Prairie Soil Carbon Balance Project (PSCB) which was initiated by the Saskatchewan Soil Conservation Association, can be used in shaping the proposed soil observation network. Attributing resources to a limited number of fields can provide good and high-quality datasets which are more valuable. Benefits/incentives to the field managers/producers should be considered.
14. The Observation network is a huge challenge, but this is the best approach/idea for measuring SOC and there are not many alternatives.

15. The goal of the datasets in the long term will be open source, but if the researchers have not published them, then they will be restricted. The project can look into the existing datasets and build on that by adding more datasets in the future. Research to obtain new datasets can be directed by a gap analysis with priority given to those gaps that are most important to fill.
16. Government stays away from cloud-based data storage (for now), but the Online Machine Learning data sharing options could be interesting to the government. If this is managed/hosted by a non-profit it may be easier to gain investment, and governments would be happier to support.
17. A potential issue with the government as the host for the data repository is the red tape and time associated with data-sharing agreements.
18. The role of government should be carefully considered as the government is susceptible to policy changes.
19. Private sectors are also susceptible to policy changes. Some sort of shared data hosting could be a good solution to mitigate the impacts of policy changes.
20. CFGA is trying to show some leadership roles in this space and CGFA will move forward with the recommendations to implement the next steps.
21. ABMI has strong expertise and experience in developing large-scale monitoring and data management programs and could play a role in the development of the data collection, management, and processing protocols and monitoring strategy.