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DISCUSSION PAPER

Standardized GHG Accounting for Soil Organic Carbon Accrual on Non-Forest Lands: Challenges and Opportunities

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About this document

This paper is meant to take stock of the current "state of play" with respect to the creation of tradable offsets to incentivize building soil carbon in non-forested soils. The document discusses the potential for developing a carbon offset protocol for soil organic carbon (SOC) accrual. The document first discusses challenges, including quantification, permanence and additionality. Then, new technologies and approaches are presented as options to overcome the challenges, and there is a short overview of how some offset programs are addressing SOC. We conclude the document with a general description of the approaches that could be used in a Reserve SOC protocol.

Executive summary

Soil organic carbon (SOC) sequestration practices have a high potential for GHG emission reductions, but these practices remain underutilized by carbon offset programs due to several challenges, including costs, uncertainty, permanence, and additionality. This document evaluates the potential for developing a Reserve SOC accrual protocol that is applicable to the United States, Mexico, and Canada. Potential practices would increase carbon stocks mainly in cropland and grassland, and would include conservation tillage, efficient irrigation, sustainable grazing, nutrient management, and cover-cropping.

There are several technologies in use and in development to achieve certain and cost-effective quantification at varying degrees. Traditional lab-based dry combustion methods combined with bulk density tests are the gold standard for SOC quantification, but direct sampling and laboratory analysis are costly and time intensive. Project level, process-based modeling support SOC quantification at multiple scales while limiting the requirement and costs of performing soil sampling and quantification approaches. However, their usage requires high technical and expert knowledge that come at such costs that prohibit project development. Standardized emission factors simplify project development but are generally limited in their applicability and involve high up-front costs and data needs.

The 100-year permanence requirement for land-use offsets limits the feasibility of offset crediting for SOC management practices. Carbon in soil is highly dynamic and farmers require management flexibility, impeding their ability to commit to long-term management changes. The use of 100-year legal contracts to ensure continued project monitoring implementation may be impossible for SOC accrual projects on actively-managed agricultural lands.

Offset programs employ different approaches to ensure project additionality. The Reserve's "top down" approach, where standardized performance requirements must be met by projects in a common group, region, or industry makes it fairly straightforward and objective for a project to assess eligibility. However, such approaches are typically narrow in scope and may exclude projects that are, in fact, additional. The common practice and proportional additionality approaches while simple in application, may let in projects that are not additional.

Several options and technologies are evaluated in this document to address the key challenges for the development of a SOC accrual protocol, including:

- The use of portable spectroscopy to measure SOC content,
- The use of remote sensing to estimate organic carbon changes,
- Advanced stratification to reduce sampling intensity,
- Predictive SOC mapping through machine learning to reduce sampling intensity over time,
- Exclusion of practices with uncertain CH_4 and N_2O emissions, which may require expensive modeling,
- Aggregation to reduce sampling intensity and reduce project development costs,
- Tonne-year accounting to reduce the timeframe of the permanence commitment while ensuring permanence of credited emission reductions,
- Potential discounting approaches to ensure permanence,
- Linking additionality to the change in SOC rather than practices, and
- Requiring the adoption of a suite of practices to ensure project additionality.

The approaches adopted by other offset programs are explored as examples of how to address quantification, permanence, and additionality issues. The list is not comprehensive and includes Australia's Emission Reduction Fund Offset Program, the existing VCS SOC accrual methodologies, COMET-Farm, the Ecosystem Services Marketplace Consortium, and the Terraton Initiative by IndigoAg.

We conclude the document with a call to other programs, experts, and stakeholders to continue this discussion and determine whether there is a clear path forward to the development of a standardized Reserve offset project protocol for soil carbon accrual.

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1 Introduction

Soil organic carbon (SOC) sequestration and conservation has garnered increased attention from the climate change mitigation community as one of the most widely available and least costly tools for greenhouse gas (GHG) emission reductions. Soils contain one of the largest organic carbon stocks on the planet with close to 1 billion metric tons of carbon to a depth of 1 meter.[1] The Reserve's Grassland Project Protocol taps this opportunity by incentivizing the avoidance of grassland conversion through the issuance of GHG offsets for the establishment of conservation easements.

What remains untapped is the opportunity to foster additional C sequestration in soils to further mitigate fossil GHG emissions. Decades, or even centuries, of intensive agricultural activity has depleted the historical SOC pools in soils around the world. However, these agricultural soils have the capacity for SOC to be rebuilt to their pre-agricultural conditions, if managed appropriately.[2] According to the IPCC, increasing soil organic content is a "large impact mitigation option" due to its capacity to reduce global emissions by at least 3 Gt CO_2 eq per year.[3] Knowledge, financial, and institutional gaps and challenges exist with upscaling and the widespread deployment of soil carbon management options.[3] Evidence suggests that incentives may be necessary to induce farmers to overcome barriers to practice changes necessary to rebuild belowground SOC pools. *Ex post* and *ex ante* carbon mitigation assets such as carbon offsets or Forecasted Mitigation Units (See section 1.2) traded in environmental market-based mechanisms may provide the necessary incentives to foster the adoption of sustainable land management practices that increase SOC.

As discussed in Section 4, several programs already exist to create tradable offset credits from soil carbon accrual projects. However, these approaches are not without their weaknesses, and none have managed to approach the scale needed for soil carbon projects to make a significant contribution to carbon markets globally. The Reserve, through this paper, is interested in taking stock of the current "state of play" of creating tradable credits to incentivize soil carbon sequestration on non-forested soils, exploring the challenges and potential ways to overcome these challenges.

1.1 SOC accrual as an offsets protocol

In line with the interest of the global community to foster SOC accrual for climate change mitigation, the Climate Action Reserve seeks to evaluate the potential for developing a SOC management protocol. The challenge lies in delivering a scalable approach that aligns with the Reserve's commitment to high quality offset principles of conservativeness, additionality, permanence, and preference for standardized approaches. We would like to know whether current policy and technology approaches can support a standardized voluntary offset protocol under which projects can be developed at a reasonable cost in relation to the potential revenues.

[1] Batjes NH. Total carbon and nitrogen in the soils of the world. Eur J Soil Sci. 1996;47:151–163.
[2] Lal R. Restoring soil quality to mitigate soil degradation. Sustainability. 2015;7:5875–5895.
[3] Olsson, Lennart, et al. "Land Degradation: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems." (2019): 1-1.

We are also interested in the potential for a SOC accrual protocol to be developed in a way which could meet the needs of the California compliance offset program. With the passage of California's Assembly Bill 398, the California Air Resources Board (CARB) is required to establish a Compliance Offset Protocol Task Force for supporting the approval of new offset protocols under California's Cap and Trade Program. Soil health and incentives for improved agricultural management practices are both important goals at CARB, so we believe there would be keen interest in a standardized SOC accrual protocol.

1.2 Implications of a SOC protocol for *ex ante* Forecasted Mitigation Units

In 2019 the Reserve launched Climate Forward, a new program focused on *ex ante* crediting for GHG emission reductions. Under Climate Forward, estimated GHG reductions from the mitigation project are recognized as Forward Mitigation Units (FMUs), which are each equal to one metric ton of CO_2e expected to be reduced or sequestered. FMUs can be retired for multiple purposes, including for CEQA mitigation or for other, forward-looking, voluntary mitigation purposes.

If a project activity is found to have high up-front implementation barriers but low operational and monitoring barriers, the project type may be more suitable for *ex ante* crediting. A key feature of this *ex ante* approach is that it credits all of the projected emission reductions for the crediting period of a project up front, provided suitable mitigation measures are put in place to minimize the risks that projects will not perform as projected. Given that SOC builds up very slowly over time, the up-front crediting in this *ex ante* approach is particularly appealing in the context of SOC accrual. This attractiveness must be balanced against the notion that *ex ante* approaches potentially exacerbate (or certainly don't alleviate) the key SOC risk of permanence, as we would need to assume that practices and conditions will remain stable for very long periods of time. In the context of working lands, where operators must respond to complex and changing conditions, caution with respect to permanence needs to be paramount.

While the focus of this scoping effort will be primarily on a protocol for *ex post* crediting, we mention the concept of *ex ante* crediting only to indicate that we will keep it in mind as an option.

1.3 Scope of consideration

We believe it makes sense to concentrate scoping efforts on certain geographical regions, eligible practices, land classifications and land use types, as protocol development resources are always finite, and necessary protocol components (such as quantification methods, and standardized additionality assessments) are not always fungible across these key elements. At this time our focus is on croplands and grasslands in the United States, Mexico and Canada. SOC improvement practices that should be considered when reading this document are any that increase carbon stocks, such as conservation tillage, conversion from cropland to grassland, more efficient irrigation or fertigation practices, sustainable grazing practices, nutrient management, and cover-cropping, among others. It would also be useful to consider if biochar or enhanced weathering applications can be included as eligible practices without significantly expanding eligibility guidelines or quantification methods used to capture SOC changes. This scoping paper should not be thought as applicable for SOC increase in forested lands, wetlands (except perhaps ephemeral wetlands with mineral soils), peatlands, urban land, and developed land.

Sustainable land management practices that increase SOC deliver other benefits such as increased water capture, improvements in subsoil water quality, increased crop resiliency, higher crop yields, and biodiversity habitat improvements, among others. While these climate mitigation co-benefits are relevant, (and we will strive to include recognition of such benefits in any protocol) this scoping paper will only focus on the GHG emission reduction benefits of SOC accrual.

2 Key components and challenges

GHG offset protocols require highly accurate and conservative SOC quantification methodologies to deliver high quality tradable offsets. As the Reserve abides by strict principles of additionality, permanence, and conservativeness, the quantification results of soil carbon sequestration must be highly accurate and highly certain (or at least with a level of uncertainty that can be estimated and managed in a reasonable manner). "In general, there is an inverse relationship between [GHG accounting accuracy and cost], and thus designing the most appropriate quantification approaches will to some degree involve determining an acceptable tradeoff between accuracy, precision and cost."[4] Below we present key components that need to be addressed to develop a rigorous standardized SOC accrual protocol with the Reserve: Accurate and cost-effective quantification, permanence and additionality.

2.1 Quantification and monitoring

The principle of conservativeness in GHG offset quantification is relevant to ensure real environmental benefits through the transactions of GHG offsets. Trading inaccurate amounts of GHG offsets would cause environmental damage through a net increase of emissions to the atmosphere. A buyer of an offset from a project whose benefits have been overestimated would increase their emissions by claiming non-real reductions.

2.1.1 Carbon measurement approaches

Critical to the success of offset projects is the ability to reliably and cost-effectively quantify SOC stock changes (and verify such changes). "However, depending on the accuracy required, the acceptable level of uncertainty, and the allowable costs for measurement and monitoring, the quantification approach will vary."[4] With all of the methods described below, cost and uncertainty are significant, to varying degrees, and depending on the use case.

Section 3 in this paper will describe three different approaches for carbon measurement to then discuss the implications of these approaches for cost and certainty, and how data availability affects applicability of some approaches.

Direct measurement of soil C stock changes

The best proxy for measuring carbon removals from the atmosphere is the measurement of change in carbon content in the soil through the extraction of samples that are measured in a laboratory often through 'dry combustion' analyzers. "The collection, transportation, and processing of soil samples adds considerable time and cost."[4]

[4] Paustian et al., 2019. Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. Carbon management. Available at https://www.tandfonline.com/doi/full/10.1080/17583004.2019.1633231.

The dry combustion process is the most accurate test for soil carbon and less costly than other tests. It involves the oxidation and measurement of total soil carbon: organic matter, charcoal, and carbonates.[5] However, "[m]ost research indicates that change in soil carbon occurs in the soil organic matter fraction, so that if you detect change, it is likely to be in the organic carbon."[5] The instrument heats a small sample (usually a fraction of a gram) of dry pulverized soil to around 900 °C and measure the CO_2 gas that is a combustion product, with results expressed as the percentage of carbon in the sample. Other soil carbon measurement approaches are acid treatments, loss on ignition and Walkley-Black, carbon fractions, soil respiration, and bulk density.[5] As dry combustion is considered the "gold standard" of carbon measurement, we will consider this method the reference point for other SOC quantification approaches discussed in this document.

Along with the determination of the fraction of SOC in dry soil, it is necessary to determine the soil bulk density to define the carbon density in the soil. The test for bulk density consists of drying a sample of soil with known volume to remove all moisture, and then weighing it. The bulk density is the dry weight in grams divided by the volume in cubic centimeters.[5]

Beyond the direct costs, another challenge to direct soil quantification approaches lies in their extrapolation to a field or landscape scale. While SOC quantification is highly accurate for the specific point of sampling, that one result has limitations to the surface and depth of a particular field that it can be used to represent. To represent soil carbon change over time in a field or landscape, multiple samples are needed which, depending on the project economics, would make this measurement approach cost prohibitive. This need for multiple samples introduces a new variable: sampling design. Additional effort and uncertainty arises from the need to determine where and how many samples should be taken for a particular project area.

Project level process-based modeling to predict SOC changes

"Models provide a means to predict SOC stock changes, taking into account the integrated effects of different management practices, as well as impacts of varying soil and climate conditions."[4] "Process-based models generally take the form of computer simulation models that employ sets of differential equations to describe the time and space dynamics of soil organic matter (SOM)". [They are] predictive tools to support SOC quantification at multiple scales.[4] Some examples include DNDC, ROTHC, APSIM and DAYCENT (for more information see Paustian et al., 2019 in Appendix A). Models can be used to predict the carbon growth in the soil due to adoption of management approaches. While these models are the preferred method for many offset programs, their usage requires high technical and expert knowledge which come at such high costs that can prohibit project development. There also needs to be sufficient data that is relevant to the project area and practices in order to ensure the model is calibrated for the specified purpose. Another issue to consider is that such models are sometimes designed to be applied at larger scale, or at least not to project level scale, at the levels

[5] Donovan, Peter. "Measuring soil carbon change." A flexible, practical, local method (2012).

of accuracy needed in the context of offsets, where the emission reductions are used to offset accurately quantified levels of emissions elsewhere.

Standardized emission factors

An approach that has been developed to reduce modeling costs and technical skill requirements for project development, is the use of standardized emission factors created with process-based models. Rather than require project developers to use biogeochemical models themselves, this approach provides the project developer with emission factors to be applied to the project based on their particular project conditions. The Climate Action Reserve's Grassland Project Protocol, for example, makes available emission factors based on the DAYCENT model, that vary depending on the project's soil texture, land use history, climate and other characterizations of regional conditions.[6] The methodology and standardized baselines are intended to provide accurate estimates of baseline emissions, give certainty over expected project outcomes, minimize project setup and monitoring costs, and reduce verification costs. The resulting emission factors preclude the need for project-level modeling. As a result, the Reserve's Grassland protocol has greatly reduced the need for historical data, and requires as few as five data points to calculate emission reductions on an ongoing basis. However, in order to run models to create emission factors, certain parameters must be "baked in," and cannot be variable between or within projects. This means the scope of pre-modeled emission factors is likely to always be narrow, and are not appropriate for every project activity.

Another approach to standardized emission factors involves empirical models, rather than process-based models. In this approach published data area used to develop emission factors that can be applied to projects without the need for project-specific modeling. This approach also suffers results in factors that tend to be narrow in scope, applying only where it can reasonably be assumed that conditions are similar to those in the studies from which the factors were derived.

2.1.2 Data availability

"A fundamental concern for any type of SO[C] modeling is the quality and quantity of available measured data to support modeling efforts."[7] SOC models require data for their formulation, calibration, driving, and evaluation. These four components of SOC models are sensitive to data limitations and determine the quality of modeling results. [C]arbon offset standards require the use of SO[C] models that have proven their applicability to the specific project being evaluated, requiring close engagement with experts in model use as well as the collection of sufficient data to accurately parameterize, drive, and evaluate the model."[7] The lack of sufficient local and regional data to calibrate, drive, and evaluate a model for accurate quantification of offset projects can hinder the possibility to use process-based models in a SOC accrual project.

2.1.3 Costs

[6] Climate Action Reserve. Grassland Project Protocol Version 2.0. (2017) Available at: http://www.climateactionreserve.org/how/protocols/grassland/

[7] Campbell, Eleanor E., and Keith Paustian. "Current developments in soil organic matter modeling and the expansion of model applications: a review." *Environmental Research Letters* 10.12 (2015): 123004.

All offset projects face a common set of transaction costs, which can greatly limit uptake of projects. These typically include costs to implement the activity in question (for instance tree planting costs, or costs to construct a dairy digester etc.), and monitoring, reporting and verification (MRV) costs. The former costs are perhaps reasonably considered to be sunk costs, implicit in the project type itself, whereas the latter are things the offset program could effectively mitigate through more efficient program and protocol design. For quantification approaches that use process-based models, adding new practices that are eligible to generate offsets can add significant complexity, so information on implementation costs can inform decisions to include/exclude eligible practices. By way of example, some evidence suggests costs of establishing riparian buffers at approximately $700-$2000 per acre,[8,9,10] and costs of forage and biomass planting at approximately $720 per acre.[11] Such costs need to be weighed against the potential benefits of including these practices.

Offset programs can employ measures to reduce MRV costs, such as by facilitating aggregation of multiple areas of land into larger projects, or standardizing MRV requirements as much as possible, both of which can create greater efficiency. Other programmatic measures to reduce cost include reducing the frequency of requisite verification activities (e.g., setting a minimum verification frequency and/or site visit requirement, of 5 years, instead of the annual or bi-annual requirement for most project types).

For a SOC project, MRV costs depend on the level of certainty required of quantification. The higher the certainty required, the higher number of samples required (and lab test costs) or the higher the technical needs (and expert salary fees) for accurate SOC modeling. Verification of quantification through process-based models significantly increases the cost of program development, as verification bodies would be required to have a staff member, or at least a subcontractor, with technical capacities to model SOC content at the same level of certainty as the project developer. In the forestry context, our experience tells us that it may be reasonable to expect costs of approximately $50/acre for inventory development and $20-$50/acre for verifications. However, SOC accrual may occur at a rate that is an order of magnitude lower than C accrual in forest biomass.

2.1.4 Uncertainty

At the soil sample level, the precision (Coefficient of Variation or standard deviation) of SOC measurements through the dry combustion method ranged from 1.3 to 7.1% according to several studies reviewed by Goidts et al., 2009.[12] Indirect Bulk Density analyses (radiation and

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[8] USDA-Natural Resources Conservation Service. Found: https://efotg.sc.egov.usda.gov/references/public/OK/CostSenarios_390RiparianHerbaceousCover.pdf. Accessed: July 2016.
[9] USDA-Natural Resources Conservation Service. Found: https://efotg.sc.egov.usda.gov/references/public/NM/CostSenarios_390-Riparian_Herbaceous_Cover.pdf. Accessed: July 2016.
[10] USDA-Natural Resources Conservation Service. Found: https://efotg.sc.egov.usda.gov/references/public/MO/MO390RiparianHerbaceousCoverFY15.pdf. Accessed: July 2016.
[11] University of California Cooperative Extension. 2003. Sample Costs to Establish and Produce Pasture. Found: http://coststudyfiles.ucdavis.edu/uploads/cs_public/3e/0f/3e0f1a8c-75b2-437e-8370-1cdfed476664/pasturesv03.pdf. Accessed: July 2016.
[12] Goidts, Esther, Bas Van Wesemael, and Michel Crucifix. "Magnitude and sources of uncertainties in soil organic carbon (SOC) stock assessments at various scales." European Journal of Soil Science 60.5 (2009): 723-739.

regression approaches) can add an uncertainty from 9% to 36% to the SOC stock measurement.[12] Thus, just the laboratory analysis of each soil sample (by dry combustion and bulk density analysis) could be introduce 10.3% to 43.1% uncertainty into the quantification, before even considering uncertainty related to sample design.

In statistical sampling, the required accuracy of results and limits on sample variability determines the number of soil samples needed at the field and landscape scales. There is a tradeoff between high levels of confidence or statistical power on the one hand, and time and expense on the other. A key challenge for direct soil measurement approaches when dealing with a carbon offset project is designing statistically effective sampling methods while limiting the time and effort in sample processing and analysis. This is particularly relevant because soil carbon needs to be measured in a mass per unit area to a specific depth.[4] Paustian et al. list further details of the challenges of direct carbon sampling and measurement:

- SOC stocks have high spatial heterogeneity that would require up to 100s of samples using simple randomized and/or stratified sampling schemes for an accurate estimation of the average SOC content across fields.[4] This adds costs and time to the analysis of the SOC.
- The full depth to which samples should be taken depends on what type of management system is being evaluated because different practices (e.g., crop and tillage type) can manifest changes over different soil depths.[4] This means that more than one soil sample may be required per sample location to accurately reflect SOC vertical gradients.
- "[M]easurement intervals of 5 years or more are required to detect statistically significant cumulative SOC stock changes from management approaches." This means that for a project developer to receive a significant incentive from practice adoption, a minimum wait period of five years may be necessary, which may be beyond the time investment a project developer would be willing to make at the beginning of the project.

The VCS *VM0021 Soil Carbon Quantification Methodology* (discussed in detail below), allows for the use of IPCC default emission factors for pools for which GHG fluxes are expected to be 0-5% of total project GHG Impacts (i.e., de minimis). The uncertainty associated with such emission factors are significant, with variability ranging from +/- 55% to 465%. Given the pools in question are de minimis, it would seem reasonable to include such pools/emission factors where it would be conservative to do so (i.e., where inclusion decreases emission reductions), but to otherwise exclude them. It would be equally reasonable to omit them under all conditions.

For our Nitrogen Management Project Protocol (NMPP), the Reserve employs Tier 2-style standardized parameters and emission factors, which were developed using the DAYCENT model, combining data from a range of national sources. A full description of the methodology underlying the development and use of the NMQuanTool can be found in Appendix F of the NMPP.[13] Half of the combinations of eligible emission factors had uncertainty ranges of between +/- 45%. The largest uncertainty ranges were associated with atypical combinations (areas with the least amount of field data available on crop production), that had the lowest N_2O impacts per acre, and in all cases the NMQuanTool automatically factors the uncertainty range to provide

[13] The Reserve's Nitrogen Management Project Protocol V2.0 is available for download here: http://www.climateactionreserve.org/how/protocols/nitrogen-management/.

the lowest emission reduction results, thus ensuring the impact of such uncertainty is conservatively reflected in emission reduction estimates.

For our Grassland Project Protocol (GPP), the Reserve employs pre-modeled, standardized emission factors.[14] For this protocol we were not able to develop quantified metrics for the uncertainty associated with specific emission factors, and so standardized discounts were developed that we believe will be conservative without being punitive. Appendix B of the GPP provides a qualitative discussion of the sources of uncertainty in the GPP.

2.2 Setting baselines

Even if a protocol is designed with a cost-effective, scientifically-defensible, and verifiable approach to monitoring and quantifying SOC pools in the project area, there still remains the task of converting those measurements into a quantity of emission reductions to be issued as credits. This requires comparing a baseline scenario to a project scenario. Quantifying the baseline scenario for a SOC project may follow one of several approaches, none without its shortcomings:

- Single point-in-time measurement of the pool at project initiation
- Detailed modeling of baseline SOC pool over crediting period based on existing management practices
- Establishment of a baseline SOC trend based on measurement at two points in time
- Paired SOC measurement at "control" properties as a proxy for baseline conditions at the project area

Each of these approaches will have different levels of cost, complexity, conceptual validity, and statistical rigor.

2.3 Permanence

For a carbon offset created from the removal and storage of a tonne of carbon from the atmosphere to be considered permanent, it must be protected in a pool related to the project activity for at least 100 years.[15,16,17] This presents one of the most significant barriers to the development of SOC accrual projects on actively-managed landscapes. Carbon in soil is highly dynamic, and it is difficult to ensure the carbon will remain stable for such the necessary time period. Similarly, farmers' choices for land management are generally variable from year to year, making it risky for the farmer to commit to specific long-term management approaches. The traditional Reserve approach to ensure carbon permanence, except Improved Forest Management projects, has been to establish permanent conservation easements on the GHG project land and/or to sign Project Implementation Agreements, which ensure continuous project

[14] A detailed methodology underlying development of standardized emission factors for the Grassland Project Protocol can be found in Appendix B of that protocol, which can be downloaded from the Reserve website here: http://www.climateactionreserve.org/how/protocols/grassland/.
[15] Fearnside, Philip M., Daniel A. Lashof, and Pedro Moura-Costa. "Accounting for time in mitigating global warming through land-use change and forestry." Mitigation and adaptation strategies for global change 5.3 (2000): 239-270.
[16] Griggs, David J., and Maria Noguer. "Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change." Weather 57.8 (2002): 267-269.
[17] Fearnside, Philip M. "Why a 100-Year Time Horizon should be used for Global Warming Mitigation Calculations." Mitigation and Adaptation Strategies for Global Change 7.1 (2002): 19-30.

monitoring. In the context of working lands, establishing such traditional commitments may be more difficult, if not impossible.

2.4 Additionality

A SOC accrual protocol needs to ensure that all sequestration is additional, in other words that the atmospheric carbon removal enhancement would not have occurred in the absence of the project. To determine additionality of offset projects, the adopted practices must be different to what would have happened in a baseline scenario. There are two common approaches to the assessment of additionality. The first is "bottom up," evaluating the adoption of practices at the project level. This can be done through approaches such as an assessment of financial barriers, which look at the need for the offset income to implement the practice in a cost-effective way. Project level additionality assessments can be time consuming, contributing to project development costs, in circumstances where project economics may already be challenging. They can also introduce significant subjectivity to the additionality determination, introducing the possibility of "gaming," whereby project-level narratives and evidence can be tailored to the specific additionality test.

The second approach, used by the Climate Action Reserve, is "top down," using standardized assessments of additionality across an entire industry, sector, or land type. Under this approach, standardized performance requirements must be met by projects in a common group, region or industry, in order for each project to be considered additional. A central benefit of such an approach is that it makes it a fairly simple process for projects to demonstrate additionality. It also provides a more objective standard for the assessment of individual projects. The downside of such an approach is that the end result tends to be narrow in scope in order to minimize the number of "false positive" determinations of additionality (i.e., allowing non-additional projects), and thus increasing the number of "false negative" determinations of additionality (i.e., excluding truly additional projects).

There are different approaches to standardized additionality assessments. The common practice approach and proportional additionality have both been used by SOC accrual protocols in the past. Under a common practice approach, if a practice is undertaken by no more a certain percentage of farmers in a particular region (commonly 5%) it can be treated as additional. A balance typically needs to be made between excluding some early adopters (often seen as unjustly penalizing critical early movers), as they may have implemented the activity without an offset motive, and rewarding laggards (those who "should have" already adopted the GHG-reducing practices, but for some reason have not). Common practice additionality approaches require periodic updates to recalibrate eligibility thresholds. Assessing common practice is often more difficult with land management projects, as it becomes difficult to hold constant many variables in order to correctly define common practice.

A second approach is proportional additionality. In this approach a sector-level benchmark, based on existing levels of adoption for a particular practice, is set as the baseline. Any project that enlists with this type of additionality would have their emission reductions discounted by a percentage equivalent to the benchmark level (i.e., if 30% of farmers have adopted the practice, everyone is eligible, but every project is discounted by 30%). This way, any project that started before or after protocol commencement can enlist although some are in reality more additional than others. The application of the discount to the overall program emission reductions, allows every project to contribute to offset additionality. A drawback to this approach is that the projects most likely to be submitted are those which would have happened anyway (i.e., they should be discounted 100%). So, the Benchmark may or may not represent an appropriate discount. This risk may be overcome if the project type is widely adopted, ensuring that actual practice change is occurring on the scale envisioned by the discount.

3 Potential options and technologies to address key components

3.1 Portable spectroscopy as an alternative to traditional SOC laboratory analysis

An alternative that has been developed to reduce the sampling and analysis effort required by direct carbon measurements are portable spectroscopic techniques. "Spectroscopic techniques measure how soils interact with light radiation of various wavelengths and yield information on SOC content as well as other chemical and physical properties of the soil."[18] "Results from spectroscopic methods must be carefully calibrated for different geographic areas and soil types using dry combustion methods [(i.e., laboratory testing)] as a reference."[4]

Yale Quick Carbon has "developed a soil carbon measurement protocol that makes use of low-cost field reflectometers…These affordable, pocket-sized devices measure soil carbon using the reflectance of soils in the visible and infrared spectra. As carbon content increases, a soil's color darkens, giving it a slightly different spectral signature than soil with lower carbon content. Standard benchtop spectrophotometers used in similar work cost ~$65,000 and are either not portable or very cumbersome, whereas this device can be produced for an order of magnitude cheaper."[19] Yale Quick Carbon's reported that in their initial field tests they were able to estimate total soil carbon with accuracies from +/- 0.2% in Oklahoma to +/- 0.5% in California. [19]These results would imply that the Yale Quick Carbon methodology has a higher accuracy than the dry combustion method However, other authors have reported that spectroscopic methods would result in reduced accuracy in comparison to conventional field measurements.[4] Further information about the comparison between traditional SOC measurement approaches and Yale Quick Carbon could help elucidate the tradeoffs between traditional carbon measurement methods and newer approaches like Yale Quick Carbon.

This technology is still under development. The Yale Quick Carbon team is refining the necessary number of bands to bring to the field as these are limited for a handheld device, measurement calibrations with soil samples are being tested to reduce uncertainty, and it is being determined how to pair the analysis with bulk density analyses to define carbon density in the soil. Portable spectroscopy also requires the use of a portable sample dryer, since samples must be of uniform moisture content for accurate results.

[18] Bellon-Maurel, V., McBratney, A., 2011. Near-infrared (NIR) and mid-infrared (MIR) spectroscopic techniques for assessing the amount of carbon stock in soils – Critical review and research perspectives. Soil Biology and Biochemistry 43, 1398–1410. In Paustian et al., 2019

[19] Yale Quick Carbon. What we do. Available at: https://www.quickcarbon.org/what-we-do.

3.2 Estimation of organic carbon changes using remote sensing

Various approaches and technologies have been deployed for a number of years to experiment with the remote sensing of SOC. Some research suggests that the soil reflectance spectroscopy technology of the kind employed by Yale's Quick Carbon can be deployed via remote sensing, for instance via satellite mounting, or even aerial drones.[20] Other research suggests that remote sensing of above ground vegetation, such as through normalized difference vegetation index (NDVI) can also be used in determining soil carbon.[21] Further research has demonstrated that SOC volumes can be estimated using algorithms of vegetation cover mapping based on Landsat satellite imagery, and various other data.[22] It appears that additional research is necessary to confirm the efficacy of these methods and prove their applicability across different landscapes, timescales, and management practices in North America.

3.3 Stratified sampling

Stratification is the division of the project area to be sampled into vertical layers or horizontal zones likely to have uniform conditions based on slope, vegetation cover, management practices, history, or other variables. Stratification may give better resolution and confidence without increasing the number of sampled plots, and thus costs. In an ideal sampling approach, variability within strata is minimized and between strata is maximized. In addition, the variables upon which the project area is stratified should be strongly correlated with soil carbon change.

Development of any stratification regime is only as good as its statistical basis, as well as the data used for the stratification. For example, stratification based on soil type (a common approach) is only effective if the soil types have been accurately mapped on the project area. This can be difficult at scale, as many parts of North America have soil maps that are only considered accurate on a regional scale, but not necessarily at the scale of an offset project.

The Australian SOC protocol uses an approach whereby Carbon Estimation Areas of uniform management conditions are defined across the project area. It is assumed that there is no SOC content variability throughout a Carbon Estimation Area and therefore 3 random sites are selected and combined to measure the carbon content in one CEA. By defining uniform areas, the number of samples required to quantify carbon across a project area is reduced while increasing the certainty of SOC measurements across a landscape.

One approach to decrease both the costs and uncertainty related to sampling design is to increase the number of datasets, including many that are remotely sensed. Such an approach requires additional computing power, but could ultimately prove to be more cost effective by producing more accurate stratification, thereby reducing uncertainty and, potentially, sampling intensity.

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[20] See, for instance, recent research available online at https://www.mdpi.com/2072-4292/11/6/676/htm and at https://www.sciencedirect.com/science/article/pii/S0034425718304267.
[21] See, for instance, recent research using Bare Soil Index, and NDVI available online here: https://www.tandfonline.com/doi/abs/10.1080/10106049.2017.1381179, and research using NDVI available online here: https://www.mdpi.com/2072-4292/11/14/1683.
[22] See research available online here: https://www.researchgate.net/publication/323190701_Mapping_of_Vegetation_Cover_and_Soil_Carbon_Stock_Using_Geographic_Information_System_Tools_Remote_Sensing_Data_and_Digiatal_Elevation_Model.

3.4 Predictive SOC mapping through machine learning

Pedometric or predictive soil mapping has been developed as an alternative to traditional soil mapping that is quantitative and objective rather than empirical and subjective. Predictive soil mapping captures relationships between soil properties (e.g., SOC), and controlling environmental influences or co-variates (e.g., climate, slope, soil texture, etc.) using statistically-formulated expressions. Pedometric models are preferred by many soil cartographers because, by design, they minimize the variance between observed and predicted values at all locations. Predictive soil mapping uses machine learning to correct previously predicted values according to new sets of data collected.[23] With machine learning, the equations describing the relationships between soil properties and co-variates keep improving in accuracy as new data are collected, thus reducing the need for further sampling over time.

In the case of a SOC accrual protocol, the benefit of predictive soil mapping through machine learning would lie in the gradual reduction of soil sampling and laboratory analysis required to describe SOC change in a landscape, thus reducing project development costs over time.

3.5 Cost effectively managing practices that cause material N_2O and CH_4 fluxes

Biogeochemical models are relevant not only as a potential tool for quantifying SOC changes, but also for quantifying any significant fluxes in CH_4 and N_2O resulting from project activities. A number of activities associated with building soil carbon may give rise to fluxes in these potent GHGs, depending on local conditions. Such changes must typically be included in project level GHG accounting, unless the changes are *de minimis* (typically defined as less than 5% of overall emission reductions of the given project), or in some circumstances they can be excluded where uncertainty associated with such fluxes are too high (especially when it's conservative to exclude such impacts). For instance, any project activities causing anaerobic conditions may cause increases in CH_4 emissions that are greater than *de minimis*. Activities that involve changes in fertilization, or changes in irrigation practices, may also foreseeably give rise to material changes in N_2O fluxes.

Options to avoid having to account for changes to CH_4 or N_2O fluxes via the use of project-level biogeochemical modeling, include the use of standardized emission factors associated with such practices, or excluding projects that employ those practices. Regarding the latter, it may be possible to determine what combination of practices and local conditions are likely to result in material increases in such emissions, and thus exclude only those specific combinations. If significant resources are needed to develop standardized emission factors, it may be more cost effective to focus such efforts on practices that are expected to result in positive GHG impacts, and summarily exclude practice for which increased emissions of CH_4 or N_2O are expected. For instance, in our nitrogen management protocol, we found that certain combinations of crops and soil conditions, when combined with the implementation of no-till, tend to cause increased emissions of N_2O, at least in the first ten years of adopting no-till.[24] Thus, we excluded those certain combinations of region, crop, and practice.

[23] Hengl, Tomislav, and Robert A. MacMillan. Predictive Soil Mapping with R. Lulu. com, 2019. Available at: https://soilmapper.org/.

[24] The Reserve's Nitrogen Management Project Protocol can be downloaded here: http://www.climateactionreserve.org/how/protocols/nitrogen-management/.

3.6 Aggregation

3.6.1 Reducing uncertainty impacts

There is evidence that the higher the area of inference, the lower the per unit area sample size requirements, because much of the variability of soils occurs at finer spatial scales. In other words, "while tens of samples might be needed to adequately quantify SOC stocks for a single field, only 2 to 3 times as many samples might suffice to quantify SOC stocks for an aggregate area of several thousand acres."[25] By meeting carbon inventory confidence standards across an aggregated project area, rather than within each discreet area, aggregation reduces the sampling intensity required within each area to meet statistical confidence requirements. Projects benefit from reduced inventory costs (fewer sample plots), and/or smaller deductions for uncertainty with greater enrollment, determined in a programmatic basis. It may also be possible to reduce deductions associated with leakage risks in proportion to the number of forests or fields in an aggregate. By way of example, in the Reserve's Rice Cultivation Project Protocol, the structural uncertainty deduction associated with the use of DNDC is reduced in proportion to the number of fields enrolled in the entire program[26].

3.6.2 Reducing transaction costs

There is a presumption that by allowing multiple project areas, or multiple discrete projects, to come together in a single aggregate, efficiencies will be gained. For instance, streamlining reporting across multiple areas or projects may reduce transaction costs associated with monitoring and reporting, though empirical evidence of this is lacking. Combining projects may facilitate greater bargaining power, vis-à-vis engaging with verifiers, and perhaps also when negotiating with credit purchasers. Efficiency gains associated with aggregation could be overshadowed by costs associated with any requisite sampling, and also be any requisite site visit requirements, so complementary policies in these areas may be needed to realize such efficiency gains.

3.7 Tonne-Year Accounting

An alternative to a 100-year permanence contract is tonne-year accounting. In this approach, projects are issued offsets only for the actual atmospheric benefit generated by the project. The standard accounting for the atmospheric benefit is to credit 1% of the carbon capture per year throughout the period of 100 years. As each year the previously-credited carbon remains stored, the 1% payments from previous years accrue incremental offset revenue over time. This generates an incentive to continue maintaining beneficial soil management practices. However, tonne-year accounting may not issue significant offset revenue at the beginning of the project which may not sufficiently incentivize project participation.

A hybrid-tonne year/tonne-tonne accounting approach where shorter time commitments (e.g., 20 years) are combined with incremental percentage accrual may be the most appropriate approach for a SOC project protocol. In this hybrid approach, project developers would commit to maintaining the carbon captured in one year over a period of 20 years to receive 20% of the

[25] Conant RT, Paustian K. Spatial variability of soil organic carbon in grasslands: implications for detecting change at different scales. Environ Pollut. 2002; 116:S127–S135. (Text directly quoted from Paustian et al., 2019).
[26] The Reserve's Rice Cultivation Project Protocol can be downloaded here: http://www.climateactionreserve.org/how/protocols/rice-cultivation/.

atmospheric benefit payment up front. Then as more carbon keeps being captured on the land, the participant can choose to continue committing to 20 more years and expanding their overall commitment or to start accruing percentage benefits over time. This hybrid approach provides a reasonable timeframe commitment for project participants and higher project revenues up front while ensuring real and additional benefits to the atmosphere. Coupled with an aggregation approach that provides sufficient scale, it may be possible to overcome the negative impacts of the time-shifted issuance schedule.

3.8 Other permanence alternatives

It may be unrealistic, with the dynamics of soils and economic drivers of land management, to expect a SOC project to maintain carbon over a period of 100 years. Tradeoffs are needed to deliver GHG offsets that deliver real benefits to the environment while limiting the permanence obligations of farmers that apply SOC accrual practices. Some approaches to allow for shorter permanence periods are:

- Discount based on probability of carbon permanence: As is done with the Alberta no-till protocol, credits can be scaled down by the probability that the sequestration might be undone in 20 years (7.5 – 12.5% according to surveyed experts).
- Discount based on cost to restore lost carbon: In the Australian Carbon Farming Initiative, farmers that choose to implement a SOC project for only 25 years have their offset credits discounted by 20% to cover the government cost of recovering that lost carbon.
- Management of permanence risk at the aggregate level. It could be possible to design a programmatic approach to permanence risk, whereby the entity who manages the aggregate is responsible for the permanence, rather than the individual landowner or farmer. This insurance pool concept would need to be carefully designed to ensure it is financially viable on a long enough timescale to ensure permanence, and not devolve into a “pyramid scheme,” whereby the developer is continually seeking new projects to make up for reversals of earlier projects.
- Transition to a conservation protocol: At the time when a SOC project ends its crediting period is when the carbon can be assumed to be at its highest risk of conversion because the farmer may no longer perceive benefits from maintaining the carbon in the soil. At this point in time, a SOC project may transfer to a carbon conservation protocol such as the Reserve’s Grassland Protocol that would continue to issue GHG offsets from the avoided conversion of the land through the establishment of a permanent conservation easement.

3.9 Additionality linked to the carbon captured

As explained in section 3.3. above, determining project additionality based on the specific management practices adopted presents the risk of including non-additional projects, depending on the performance standard threshold selected (or excluding additional projects). Moreover, defining an additionality threshold is limited by the availability and quality of common practice data. An alternative to define project additionality is to define and quantify the SOC content in the soil that would be additional in comparison to a SOC reference baseline. This approach would make the additionality assessment practice agnostic. As long as the SOC in the soil increases in comparison to what the SOC would have been in the absence of the project, the practice used can be deemed additional. This approach is somewhat analogous to that employed in Improved Forest Management projects.

There are different approaches to determining the change of SOC in comparison to a baseline:

- Modeling SOC baseline: The VCS methodologies described in detail in section 5.2.1. require modeling of the SOC baseline conditions against which to compare the carbon growth in the project scenario. The difference between project and baseline SOC equates to the amount of emission reductions that can be issued to the project.
- Define linear SOC trend based on two soil samples across time: Another approach is to measure SOC through two points in time to determine a linear trend of SOC, then, based on the application of SOC management practices, whatever SOC is measured above the linear trend could be deemed additional.
- Standard SOC content baseline: Based on remote sensing and other georeferenced available data, baseline SOC content could be defined a-priori at a regional level, to which projects can compare their SOC content against. The difference between the standardized SOC baseline and the project SOC content after implementation would be the emission reduction credits to be issued. This is similar to the common practice metric for forests defined by the US Forest Service, and employed as a benchmark in the Improved Forest Management Project Protocol.
- T-test approach to define linear SOC growth: See section 4.1. below (Australia's Emission Reduction Fund).

Assessing project additionality based on the SOC content would still require the protocol to define a positive list of innovative practices that are generally considered to increase carbon stocks. This measure would ensure environmental integrity of the program and avoid carbon leakage due to practices with high CH_4 or N_2O emissions that should not be eligible.

3.10 Requiring adoption of suite of practices to ensure additionality

The implementation of one single practice presents a lower threshold for additionality than requiring a comprehensive suite of practices with the purposes of SOC accrual. An alternative to simple, individual, positive practice lists, proportional additionality, and linking additionality to SOC change is to define a protocol-specific suite of SOC accrual practices that would need to be adopted by a farmer to be eligible into the program. It would be more difficult to perceive a farm as non-additional if it starts applying no-till practices, cover crops, organic fertilizers, and efficient irrigation practices all at once to enter an offset program, than to claim additionality for the adoption of no-till practices alone. Individual practice adoption may be the result of regional trends or other economic considerations, while adoption of multiple SOC-benefiting activities continues to be rare.

4 Existing programs and methodologies

4.1 Australia's Emission Reduction Fund – Compliance Offset Program

The Australian Government's compliance offset program, the Emissions Reduction Fund (ERF), currently has one methodology dedicated specifically to soil carbon accrual, the Soil Carbon Sequestration in Agricultural Systems methodology. The methodology, like the broader program, allows projects to use either a 25 or 100-year permanence period. Projects using the

25-year permanence period are required to take a 20% discount on emission reductions issued, and make a 5% risk of reversal buffer pool contribution. Projects are allowed a maximum 10-year crediting period, and can end the project early by giving back issued credits.

The methodology requires the direct measurement of soil carbon, specifies sampling methods and lab techniques, and allows the use of calibrated in-field sensors. One or more specific activities must be undertaken as part of the project, including the application of soil amendments, fertilizer management, grazing management, irrigation changes, and tillage changes, amongst others. The method applies a temporary discount to increases in soil carbon stocks after the second sampling round, as well as ongoing uncertainty discounts. To quantify carbon growth, after the first two samples are taken, a one-tailed t-test is employed, assuming unequal variance across time to define the carbon stock change associated with a 60% probability of exceedance. Then, 50% of the carbon growth is discounted to overcome challenges in quantifying non-linear carbon growth trends. Once a third (and subsequent) sample is undertaken, a linear regression approach is used to define the rate of soil mass carbon change. The method uses a stratified simple random sampling design, with a minimum of three strata, and one sample per stratum, however it is recommended that sampling intensity is increased to ensure accuracy. Detailed guidance is given for sample collection and processing. There appear to be 44 projects currently registered under this method, though only one has been issued credits. In discussions with Reserve staff, ERF staff have indicated that the low issuance to date is likely the result of slow SOC accrual rates, with project developers thus choosing to defer verifications until those are cost effective, rather than being due to any programmatic barriers.

A recent review of the ERF prepared by the Australian Government explored a number of issues relevant to permanence.[27] The resulting report notes that for aggregated projects, participants face the risk that a failure of one of their fellow project developers may impact them, as reversal obligations are imposed across the whole project area.[27] With respect to the 5% buffer pool contribution, a leading scientific body pointed out that soil sequestration projects appear to be heavily clustered in regions, so it may be wise to revisit the standard 5% buffer contribution. A number of other views were also tabled with respect to the buffer, and ultimately the Government stated any revisions to this policy would only apply to future projects. With respect to the 20% discount on emission reductions associated with the 25-year permanence period, the report stated this deduction was meant to reflect the potential cost to the Government of replacing carbon stores if these projects are discontinued, rather than embody a tonne-year accounting approach.[27]

4.2 VCS methodologies

The Verified Carbon Standard (a program of Verra) has adopted several methodologies to account for soil carbon. At present there are six VCS methodologies that include a SOC component, as listed below.

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[27] Commonwealth of Australia (Climate Change Authority), *Review of the Emissions Reduction Fund,* 2017. Available for download here: http://climatechangeauthority.gov.au/sites/prod.climatechangeauthority.gov.au/files/files/CFI%202017%20December/ERF%20Review%20Report.pdf.

Adopted methodologies:

- VM0017 Adoption of Sustainable Agricultural Land Management (SALM) – focuses on a specific set of management practices. This methodology allows the project developer to themselves specify the quantification method they will use for SOC accrual, as long as it has been accepted in scientific publications and validated for the project region. The methodology also references a number of tools for other emissions pools, such as to measure the impacts of N-fixing species, and to measure N_2O emissions from fertilization.[28]
- VM0021 – Soil Carbon Quantification Method – adopted 11/16/2012 – includes accounting for organic and inorganic soil carbon, various types of biomass (woody, litter, roots etc), and impacts of fire.
- VM0026 - Methodology for Sustainable Grassland Management (SGM) – adopted 04/22/2014 – specific to sustainable grassland management projects where ongoing degradation is occurring and is expected to continue.
- VM0032 – Methodology for the Adoption of Sustainable Grasslands through Adjustment of Fire and Grazing – adopted 07/16/2015 - limited to activities on uncultivated grasslands where fire is a potential occurrence.

Methodologies under development (currently inactive):

- Agricultural Land Management – Improved Grassland Management – Under development (Inactive) - dependent on existence of applicable, tested soil models for determining soil carbon.
- Calculating Emission Reductions in Rice Management Systems – under development (Inactive) – specific to reducing emissions from rice cultivation

All of these methods focus on various practices that can influence SOC, and each uses a different array of methods and models, such as Century and DNDC. The VM0021 Soil Carbon Quantification Methodology is much more general and thus more broadly applicable, so further details are provided on it below.

4.2.1 VM0021 – Soil Carbon Quantification Method

This methodology was developed by Earth Partners LLC and adopted by VCS in 2012. The methodology requires the use of DNDC under certain conditions, and it "does require a significant level of technical ability on the part of the project proponent team." The methodology includes practices such as direct soil management, as well as management of hydrology, fertility and vegetation systems. DNDC must be used whenever there are expected to be significant increases in N_2O or CH_4 from baseline to project. One can anticipate that CH_4 changes may be due to anaerobic conditions, and N_2O fluxes from a much broader suite of project activities, including those that involve changes in fertilization, tillage, and hydrology (e.g., irrigation). The methodologies include significant guidance on stratification and sampling. This methodology refers to external documents for guidance and rules on key issues, including the following:

[28] See the A/R Methodological tool "Estimation of direct nitrous oxide emission from nitrogen fertilization" (Version 01) EB 33, Annex 16 here: https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-07-v1.pdf.

- VMD0018 Methods to Determine Stratification: This methodology provides extensive guidance on stratification, including on: how to initially identify relevant variables; how to identify appropriate timespan over which stratification must occur (in the case of SOC the focus would be on future processes, and how changes in those effect SOC); the selection of an appropriate stratification method; the identification of key factors; pre-stratification; the use of sampling and qualitative reviews to refine initial stratification; as well as post-stratification and re-stratification. Sampling intensity will be set based on pre-sampling work, and can be informed using statistical methods such as the CDM A/R Methodological Tool *Calculation of the number of sample plots for measurement with A/R CDM project activities* (AR-AM Tool 03 Version 02 or later version).[29]

- VMD0021 Estimation of Stocks in the Soil Carbon Pool: This methodology provides extensive guidance for accounting for both organic and inorganic soil carbon. The guidance extends to: pre-sampling; selecting sampling parameters, including sampling intensity; adjusting sampling methods to deal with changing conditions; as well as sample preparation and lab procedures.

- VMD0029 Estimation of emissions of non-CO_2 from soils: This methodology provides extensive guidance on when it's necessary to account for CH_4 and N_2O, and how to do so. The methodology requires the use of DNDC for significant fluxes resulting from project activities.

4.2.2 Permanence under VCS standards

Under the VCS, for SOC projects, the maximum quantity of emission reductions that may be claimed by a project cannot exceed the expected net GHG benefit generated by the projected 100 years after its start date (AFOLU Requirements 3.6, section 4.5.29). At the outset of a project projections must be made covering the net GHG impacts of the project over the whole 100-year permanence period, while projects can have crediting periods between 20 and 100 years (VCS Standard v3.7, Section 3.8.1).

If a project voluntarily decides to change their practices at some point between the end of its crediting period and the end of the 100-year permanence period, it appears any reversals would be covered by the buffer pool and no sanctions would be imposed on the project.

4.3 COMET-Farm

COMET-Farm is a tool developed as a partnership between the USDA's NRCS team and Colorado State University.[30] COMET uses information on various management practices together with spatially-explicit soil and climate data drawn from multiple USDA databases. The model relies on bio-geochemical process models, IPCC methodologies, and peer-reviewed research results. COMET is the official GHG quantification tool of the USDA. The model is primarily intended for landscape-scale carbon accounting, so is not ideally suited for project-level accounting of SOC impacts.

[29] Available for download here: https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-03-v2.1.0.pdf.
[30] Information on COMET-Farm can be found online at the CSU website, here: http://cometfarm.nrel.colostate.edu/.

4.4 Ecosystem Services Marketplace Consortium

The Ecosystem Services Marketplace Consortium (ESCM) is a group of stakeholders who have come together to create an Ecosystem Services Market (ESM), that pays farmers to deliver various environmental services.[31] Initially the program will measure three main attributes, net GHG impacts (including SOC accrual), water quality, and water quantity. The ESCM was initially launched by the Noble Research Institute, but since 2019 management of the work was transferred over to the newly-created Consortium, housed under the Soil Health Institute. Amongst ESCM membership are experts in the 3 focus areas, as well as buyers and sellers of the attributes.

At the core of the program is the development of a protocol, much like an offset protocol, which provides guidance on eligibility, quantification, and MRV for the three core ecosystem services. During earlier discussions, and a public webinar in February of 2019, ESCM members advised that the protocol was intended to follow a tiered approach, whereby participants could elect to choose which tiers, and thus which level of participation, they would have. Tier one would essentially be an “inset” tier, where the successful outcome would be the recognition of attributes for carbon, and the generation of water quality protection certificates, and water efficiency credits. For tier one the benefits would not necessarily be quantified in tCO_2e, or at least not to the same degree of accuracy as an offset. The MRV required, at least for the carbon component, would thus also not necessarily be as stringent as for the creation of carbon offsets. Tier two would be an offsets tier, where the successful outcome would be the issuance of tradable carbon offsets, and potentially also some form of credits for water quality improvements (such as water quality certificates), but no water quantity-related credits. Back in February there was also mention of ongoing research into possible flood reduction credits. As this information is almost seven months old, it’s possible the protocol has evolved since then. Unlike typical offset protocol development, the intent expressed by ESCM was that they would develop the protocol, and then road test it with landholders first, refine it, and then at a later stage release it for scientific peer review and public comment.

4.5 IndigoAg – Terraton Initiative

The Terraton Initiative seeks to remove CO_2 from the atmosphere and capture it in agricultural soils through implementation of regenerative agriculture practices. The initiative intends to provide incentives to farmers to switch to regenerative practices without a long-term, binding commitment nor cost to sign up. Indigo Ag intends to require the measurement of a participant’s baseline carbon content at the beginning and end of a growing season, provide technical assistance, and cover other transaction costs such as verification and monitoring.

To ensure permanence of practices, the initiative will use a *vesting schedule*, whereby the carbon captured each year will be issued over a 10-year schedule. In each year of the payout schedule, 8% is paid to the farmer and 2% is sent to a buffer pool to cover unintentional reversals. If an intentional reversal occurs the farmer is not responsible for paying the credits back, but would not be able to have more credits issued until the carbon content in the soil is brought back to the level it was prior to the reversal.

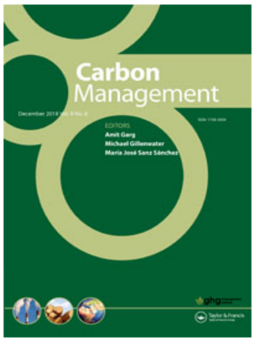
[31] See the Ecosystem Services Market Consortium website here: https://ecosystemservicesmarket.org/.

The means through which the initiative will continue to measure and sample soil content past the pilot stages are still under development. Terraton launched a challenge to identify partners to help accelerate cost-effective and scalable carbon measurement technologies that will continue to receive applications until October 1, 2019. It is our understanding that they intend to develop a voluntary offset project methodology to support the creation of GHG credits.

5 Discussion

Before embarking on development of a standardized offset project protocol for soil carbon accrual on non-forested landscapes, the Reserve should also consider whether *ex post*, project-level offset crediting is even the correct approach for addressing this carbon pool. Given the challenges to affordable measurement with scientific rigor and certainty at the project scale, this project type might be best suited for an approach that credits at a larger, perhaps regional, scale. In addition, scaling up may allow for new approaches to verification and managing permanence risk that relieves individual landowners from the need to enter into 100-year contracts committing them to certain practices. Some of the new programs discussed in this paper are taking some form of this aggregated, centralized approach to crediting. The Reserve looks forward to engaging with other programs, experts, and stakeholders to continue this discussion and determine whether there is a clear path forward to the development of a standardized Reserve offset project protocol for soil carbon accrual.

Appendix A Quantifying carbon for agricultural soil management: from the current status toward a global soil information system (Paustian et al., 2019)



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REVIEW ARTICLE

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Quantifying carbon for agricultural soil management: from the current status toward a global soil information system

Keith Paustian[a], Sarah Collier[b], Jeff Baldock[c], Rachel Burgess[d], Jeff Creque[e], Marcia DeLonge[f], Jennifer Dungait[g], Ben Ellert[h], Stefan Frank[i], Tom Goddard[j], Bram Govaerts[k], Mike Grundy[l], Mark Henning[m], R. César Izaurralde[n,o], Mikuláš Madaras[i,p], Brian McConkey[q], Elizabeth Porzig[r], Charles Rice[s], Ross Searle[l], Nathaniel Seavy[r], Rastislav Skalsky[i,t], William Mulhern[b] and Molly Jahn[b]

[a]Department of Soil and Crop Science, Colorado State University, Fort Collins, CO, USA; [b]Department of Agronomy, University of Wisconsin-Madison, Madison, WI, USA; [c]Commonwealth Scientific and Industrial Research Organisation, Adelaide, Australia; [d]Australian Department of the Environment and Energy, Canberra, Australia; [e]The Carbon Cycle Institute, Petaluma, CA, USA; [f]Union of Concerned Scientists, Washington, DC, USA; [g]Scotland's Rural College, SRUC, Edinburgh, Scotland; [h]Agriculture and Agri-Food Canada, Lethbridge, Alberta, Canada; [i]International Institute for Applied Systems Analysis, Vienna, Austria; [j]Alberta Agriculture and Forestry, Edmonton, Alberta, Canada; [k]International Maize and Wheat Improvement Center, Texcoco, Mexico; [l]Commonwealth Scientific and Industrial Research Organisation, Brisbane, Australia; [m]United States Department of Agriculture, Natural Resources Conservation Service, Miles City, MT, USA; [n]Department of Geographical Sciences, University of Maryland, College Park, MD, USA; [o]Texas AgriLife Research, Texas A&M University, Temple, TX, USA; [p]Crop Research Institute, Prague, Czech Republic; [q]Agriculture and Agri-Food Canada, Swift Current, Saskatchewan, Canada; [r]Point Blue Conservation Science, Petaluma, CA, USA; [s]Department of Agronomy, Kansas State University, Manhattan, KS, USA; [t]National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Bratislava, Slovakia

ABSTRACT
The importance of building/maintaining soil carbon, for soil health and CO_2 mitigation, is of increasing interest to a wide audience, including policymakers, NGOs and land managers. Integral to any approaches to promote carbon sequestering practices in managed soils are reliable, accurate and cost-effective means to quantify soil C stock changes and forecast soil C responses to different management, climate and edaphic conditions. While technology to accurately measure soil C concentrations and stocks has been in use for decades, many challenges to routine, cost-effective soil C quantification remain, including large spatial variability, low signal-to-noise and often high cost and standardization issues for direct measurement with destructive sampling. Models, empirical and process-based, may provide a cost-effective and practical means for soil C quantification to support C sequestration policies. Examples are described of how soil science and soil C quantification methods are being used to support domestic climate change policies to promote soil C sequestration on agricultural lands (cropland and grazing land) at national and provincial levels in Australia and Canada. Finally, a quantification system is outlined – consisting of well-integrated data-model frameworks, supported by expanded measurement and monitoring networks, remote sensing and crowd-sourcing of management activity data – that could comprise the core of a new global soil information system.

KEYWORDS
Soil carbon; carbon sequestration; measurement methods; SOC models; soil monitoring; soil health

Take Home messages:

- Increasing soil organic carbon (SOC) stocks would improve the performance of working (managed) soils especially under drought or other stressors, increase agricultural resilience and fertility, and reduce net GHG emissions from soils.
- There are many improved management practices that can be and are currently being applied to cropland and grazing lands to increase SOC.
- Land managers are decision makers who operate in larger contexts that bound their agricultural and financial decisions (e.g. market forces, crop insurance, input subsidies, conservation mandates, etc.).
- Any effort to value improvements in the performance of agricultural soils through enhanced levels of SOC will require feasible, credible and creditable assessment of SOC stocks, which are governed by dynamic and complex soil processes and properties.
- This paper evaluates currently accepted methods of quantifying and forecasting SOC that, when augmented and pulled together, could provide the basis for a new global soil information system.

Introduction

In recent years, soils have garnered increased attention for their crucial roles in food security and delivering key ecosystem services (e.g. primary production, clean water, nutrient cycling), including their capability and potential to help mitigate

CONTACT Molly Jahn molly.jahn@wisc.edu Department of Agronomy, University of Wisconsin-Madison, Madison, WI

climate change by sequestering carbon – against a backdrop of widespread soil degradation across much of the globe [1–4].

Soils contain one of the largest organic carbon C stocks on the planet, with ca. 1500 Pg C (1 Pg = 10^{15} g = 1 billion metric tonnes) to a depth of 1 m and 2400 Pg C to 2 m depth [5]. This carbon actively exchanges with the atmosphere via the processes of photosynthesis and respiration. As such a large and active C pool, small percentage changes in these stocks can greatly affect the amount of C as CO_2 in the atmosphere and the C balance at a global scale.

At the local scale, there are multiple ramifications when soils gain or lose soil organic carbon (SOC). When SOC stocks are reduced, it is typically coincident with other forms of soil degradation (e.g. topsoil loss, compaction, reduced aggregate structure) [6]. In general, agricultural soils are degraded relative to their pre-agricultural condition and therefore have a capacity for SOC stocks to be rebuilt if managed appropriately [7]. Observations from field experiments suggest that agricultural operations that have been managed to improve SOC levels also improve physical soil quality ('tilth') [8], reduce susceptibility to erosion [9] and outperform more conventionally managed systems with respect to agricultural yields and yield stability, especially under drought stress [10,11].

Soils have a crucial and obvious role to play in the global response to climate change. In the most recent IPCC assessment [12], many of the integrated assessment models for GHG reduction strategies suggest that aggressive fossil fuel reductions must be supplemented with negative emission or C sequestration options to contain warming below 2 °C as laid out in the 2015 Paris climate accords. This finding has been further supported by the recent analysis of Hansen *et al*. [13] on the need for C negative emissions, as well as Rockström *et al*.'s [14] roadmap for decarbonization. It has been suggested that, relative to other negative emission options, soil C sequestration may offer one of the least expensive and most readily implementable near-term options [15]. With widespread adoption of best soil management practices, soils can act as a global carbon sink to help achieve a net removal of CO_2 from the atmosphere [15,16]. Thus, soil C sequestration is a negative-emissions option that must be considered with the double win of improved soil properties (chemical, physical and biological) and associated agro-ecosystem health, resilience and productivity [17].

Early studies on how management might be used to increase soil organic matter (SOM) for the purpose of removing more CO_2 from the atmosphere [18] relied on field experiments [19] and models [20,21] that were originally designed to study SOM as a soil fertility factor. These early field studies and models remain relevant, and, in many ways, still represent core knowledge of SOC dynamics. However, over the past two to three decades, the development of sensitive analytical instruments allowing quantification of SOC at the biomolecular scale, along with new applications of isotopic labelling, have illuminated the myriad factors that control SOC dynamics [22–24]. While many fine-scale details regarding SOM dynamics remain to be elucidated, it is fair to say that, in general, the basic controls on gross SOC stock changes are understood and it is reasonably well known which management practices can be used to increase SOC storage across a wide range of environments. Furthermore, in spite of the complexity of SOC dynamics at the micro scale, scientists are now beginning to understand the relationship between microscale soil processes and macroscale soil structures (e.g. aggregate to peds), that respond to managed changes in SOC such that they can be used as indicators in soil health assessment protocols.

The fact that many agricultural land managers do not currently employ practices that optimize C storage, despite the widely described potential benefits, indicates the need to more explicitly incentivize these practices. Clearly, land managers can be expected to maximize economic returns and thereby focus on yields/commodity production as the conventional income-generating strategy. Increasing SOC may, in some cases, 'pay for itself' through reducing the need for purchased inputs and improving long-term soil health, thus boosting productivity even in times of relative stress, such as drought [25–27]. However, other factors such as lack of knowledge, training or technical capacity may still inhibit implementation of such 'negative-cost' improvements. In many cases, farmers do incur real, increased costs for implementing better C sequestering practices, in terms of higher input costs (e.g. seed and operations costs for sowing cover crops) and/or increased risk of declines in yield. Thus, opportunities for monetary benefits to the farmer are needed to balance the potential added costs and to drive widespread adoption of improved practices.

Currently, there are three main ways in which the value of soil C sequestration can potentially be included in direct financial returns to land managers.

First, government subsidies as direct payments or as cost sharing can incentivize farmers; examples include the U.S. Department of Agriculture's Environmental Quality Incentives Program (EQIP) and Conservation Stewardship Program (CSP) in the US [28]. Although these programs were originally designed to meet general resource conservation objectives, the practices they promote are generally compatible with C sequestration and GHG emission reductions [29], and thus enhancing the promotion of C sequestration through such programs can be accomplished with relative simplicity. Reduced rates for government-supported crop insurance programs offer an additional incentive mechanism [30]. Similarly, the European Union's Common Agricultural Policy (CAP) provides incentives for protecting soil health and function, including maintenance of SOM (and hence soil carbon storage) [31].

Second, agricultural land managers could be directly compensated for CO_2 removal and storage as SOC as a C 'offset', in which the sequestered C could be sold as a commodity to companies engaged in GHG emission reductions, in either a voluntary marketplace or a compliance cap-and-trade system. Some offset projects that include SOC are ongoing, including through dedicated registries (e.g. Verified Carbon Standard, VCS: https://verra.org/project/vcs-program/registry-system/; American Carbon Registry, ACR: https://americancarbonregistry.org/) operating in the voluntary market space. However, low C prices (often $< \$5$/tonne CO_2) have limited project development to date [32]. Government-sponsored, incentive-based offset projects and trading involving soil C sequestration are ongoing in Australia and Canada, as discussed in detail in case studies below.

Third, companies that produce and market products that are based on agricultural commodities, including food, beverages and fibers, are increasingly interested in developing more sustainable supply chains, including reducing their products' 'carbon footprint'. Diverse practice-based standards, tools and certification schemes, in addition to brand and company pledges, have proliferated to meet this demand. Hence agricultural producers could be incentivized to implement C sequestering practices by earning a premium price for producing agricultural products to achieve sustainable supply chain goals.

Critical to the success of any of these three approaches to incentivize soil C sequestration is the possibility to reliably and cost-effectively quantify SOC stock changes and affirm that they are occurring. However, depending on the accuracy required, the acceptable level of uncertainty, and the allowable costs for measurement and monitoring, the quantification approach will vary. In general, the level of rigor required and the associated cost for quantification will be greatest for offset projects in which SOC has a defined per-tonne value as a fungible commodity, whereas the least stringent requirements likely exist for participants in government programs, where payments are justified based on overall conservation benefits, not just SOC [33]. In general, there is an inverse relationship between the cost and the uncertainty of the measurements, and thus designing the most appropriate quantification approaches will to some degree involve determining the acceptable trade-off between accuracy/precision and cost.

This paper provides an overview of current methods and approaches for quantifying SOC stock change and the associated removals of CO_2 from the atmosphere. The aim is to illustrate how these methods currently apply to quantifying SOC stock changes at field to national scales, including examples of such methods applied to ongoing programs in Australia and Canada. A concept is then outlined for a comprehensive global soil information system that could support quantification, monitoring and reporting of SOC stock changes for a scaled-up effort to promote widespread adoption of soil management strategies to remove and sequester CO_2 and improve soil health.

Quantification methods

Associating CO_2 removals with soil C stock changes

Biotic carbon stocks exist in a dynamic balance between continual inflow and outflow of carbon. For promoting carbon sequestration, the *net* amount of CO_2 that is removed from the atmosphere and incorporated into the soil is the metric that matters. However, this value is the difference between two large fluxes of CO_2: the uptake of CO_2 by plants and emissions of CO_2 via respiration from plants and the soil biota. Since the net flux of CO_2 on an annual basis is often very small relative to the gross fluxes, net gains or losses of C from the ecosystem are difficult to measure accurately and routinely, requiring sophisticated research instrumentation (see the section below). An alternative approach is to track the *changes* in ecosystem *C stocks* over time. Since the predominant C exchange in terrestrial ecosystems is between the atmosphere and the plant/soil system, an increase in biotic organic C stocks over time is a close proxy for the net uptake of C (as CO_2) from the atmosphere. Conversely, in the absence of erosion or other lateral transport processes, a decrease over time in ecosystem C stocks indicates a net flux of C to the atmosphere. In forests and shrubland, considerable C may be stored in woody biomass that can accumulate and persist over many decades, and so plant biomass C must be considered in any net CO_2 accounting approach. In agricultural systems that lack long-lived woody biomass (e.g. annual cropland and non-wooded grassland), plant biomass stocks are relatively small and mostly ephemeral due to annual harvesting and grazing. Thus, the only large and persistent (from year to year) organic C stock is in the soil. Therefore, SOC stock accounting is what matters for assessing whether agricultural ecosystems are a net source or sink of C. Here, the direct measurement of CO_2 fluxes is only briefly discussed, and most of the discussion is focused on determining SOC stock changes over time.

Direct measurement – CO_2 fluxes

The most direct means to determine whether ecosystems are functioning as a net C sink and therefore acting to reduce atmospheric CO_2 concentrations is by measuring the net CO_2 exchange between the atmosphere and the ecosystem. Recent decades have seen the development, refinement and deployment of flux measurement systems, based on principles of micrometeorology, in all kinds of terrestrial ecosystems [34]. The most widely used technique, eddy covariance (EC), relies on very frequent and highly accurate measurements of CO_2 concentrations and air movements, that can be used to estimate the net gas exchange between the atmosphere and the land surface, as a result of photosynthesis (CO_2 uptake) and ecosystem respiration (CO_2 release). When combined with measurements of harvested and exported biomass, and assuming other C losses (e.g. erosion, leaching) are negligible, EC can provide an integrated estimate of net ecosystem C stock changes and valuable information on its temporal dynamics. These approaches are particularly useful for making ecosystem C balance estimates for grazed grasslands [35,36], in which livestock activities make other on-the-ground sensors difficult to maintain, particularly at the levels of replication needed to account for grazer influence on spatially varying vegetation and soil C stocks. EC techniques are also well suited for estimating net C fluxes from peat soils [37,38], which have varying density and depth of organic layers that make SOC stock changes difficult to measure. However, EC and other micrometeorological methods are (at present at least) restricted to the research environment. The techniques involve sophisticated and expensive instruments and require highly trained technical staff to manage and maintain them and to process and analyze the data. They also require several assumptions including relatively homogeneous study plots and level topography that are not always possible in manipulative field experiments or privately managed working lands. While these types of measurements are very useful for developing and validating ecosystem C models, they are not practical for routine deployment for C offset projects or in extensive farm/ranch-based measurement and monitoring networks. Rather, to meet such needs, soil sampling and measurement of SOC stock change is typically the most feasible field quantification approach.

Direct measurement – soil C stock changes

Take Home messages:

- Calculation of SOC stocks require volumetric soil samples (to estimate bulk density) which are more laborious to collect than soil samples collected for routine nutrient analyses.
- Soil samples must be dried and processed (crushed, sieved, ground) to ensure representative samples are analyzed.
- Ideally, sample preparation is followed by analysis via automated dry combustion in the laboratory. For soils that contain inorganic forms of carbon, acidification may be required to determine organic C concentration.
- Other less expensive and less precise methods of lab analyses may be considered, but often the incremental expense associated with using a modern analyzer is small relative to the costs of collecting and processing the soil samples.
- Spectroscopic methods (lab- and field-based) offer the potential for more rapid, cheaper analyses but at the cost of reduced accuracy and usually require extensive calibration.
- The main challenges to measuring SOC stocks at field-scales are high spatial variability and small changes relative to 'background' SOC stock.
- Efficient, fit-for-purpose sampling designs that employ georeferenced benchmark sites that optimize the balance between sampling intensity and reduced uncertainty can lower the cost and improve accuracy of direct measurements.

Determining the concentration of C in a soil sample is not technologically challenging or especially difficult. However, large aggregated mitigation and soil C valuation projects and policies require more than simply C concentrations determined in the laboratory; they require an estimate of SOC in mass per unit area to a specified depth, and the capability to estimate temporal changes in SOC stock associated with improved management. The main challenges in applying direct measurement methods to accurately and cost-effectively quantify soil C stock changes over time are in designing effective *sampling methods* and reducing the time and effort in *sample processing and analysis*.

Sampling methods

A major challenge in determining SOC stocks and changes at field scales is the high degree of spatial heterogeneity. Even in seemingly 'uniform' fields, SOC content may vary by as much as 5-fold or more [39]. Using conventional approaches with simple randomized and/or stratified sampling schemes, accurate estimation of the 'average' SOC contents across fields of tens of hectares might require tens to hundreds of samples [40]. In addition to lateral variability, organic C usually decreases markedly with soil depth, with the highest concentrations in the top few cm and then usually declining sharply below the topsoil layer. In some cropland soils, SOC content may be fairly homogeneous from 0 to 20 or 30 cm due to mixing by tillage, but in unplowed soils (e.g. pastures, no-till cropland) SOC typically declines more continuously from the surface. Detecting overall changes in SOC requires accounting for this vertical gradient, so measurements are usually taken from multiple depth increments (e.g. 0–10 cm, 10–20 cm and so on), and appropriate analyses to account for inorganic C, especially in sub-surface layers, are required in many regions. Thus, the full depth to which samples should be taken depends on the type of management system being evaluated because different practices (e.g. crop and tillage type) can manifest changes over different soil depth intervals. The 0 to 30 cm soil layer specified by the IPCC [41] for soil C inventories probably captures most short-term land-use and management-induced changes in SOC stocks, although some practices (e.g. cropland conversion to grassland with deep-rooted species) can have impacts deeper in the soil profile [42]. Over decadal time scales, relatively minor changes to subsoil SOC stocks that manifest under many cropping systems can constitute non-trivial quantities of C at the farm scale [43]. Because variability in SOC stocks tends to increase as a function of depth, while the impacts of most management practices on stocks tends to decrease with depth, efficient analyses of SOC changes should evaluate SOC stocks sequentially, from the surface to increasing cumulative depth layers, to the full depth of sampling [44]. This enables statistically significant differences, which may be confined to surface layers, to be revealed without diluting the signal by including non-significant differences at depth.

Finally, the amount of SOC already present in most soils, versus the amount and rate of change that typically occurs from adopting C sequestering practices, represents a typical signal-to-noise problem. Many practices advocated to increase SOC stocks do so at rates of less than 0.5–1 Mg C $ha^{-1} yr^{-1}$, whereas 'background' SOC stocks in many soils, just in the top 20–30 cm, can be in the range of 30–90 Mg C ha^{-1}. Therefore, with potential annual stock changes of 1% or less of the existing stocks, measurement intervals of 5 years or more are generally required to detect statistically significant cumulative SOC stock changes with a moderate sampling density.

Rather than using sampling designs that aim to quantify the total *amount* of SOC in a field, a more efficient and less costly approach is to measure SOC stock *change* over time at precisely located benchmark sites [45–47]. These can be resampled over time, reducing sample requirements by as much as 8-fold compared to simple random or stratified random sampling designs [48].

In addition, because much of the variability of soils occurs at fine spatial scales, *per unit area* sample size requirements decrease greatly as the area of inference increases in size. In other words, while tens of samples might be needed to adequately quantify SOC stocks for a single field, only 2 to 3 times as many samples might suffice to quantify SOC stocks for an aggregate area of several thousand hectares [49]. Accordingly, quantification approaches that require direct field measurement will be more feasible for implementation in C offset projects with many farms and aggregated areas of many thousands of hectares. Schemes that optimize the sampling intensity by taking into account the value of reduced uncertainty (i.e. as monetized in a C offset project), which is related to the number of samples taken, can further reduce costs [50].

Sample processing and analysis

Modern methods to measure SOC concentrations using dry combustion analyzers are the 'gold standard' in soil science. These automated instruments are highly accurate and widely used in soil and environmental research.

With current technology, accurate direct measurement of SOC requires 'destructive sampling' (i.e. soils taken from the field and then sent to a laboratory for processing and analysis). There are two main reasons for this. First, conventional analysis methods to determine C content as a percentage of total soil mass – that is, both dry and wet oxidation methods – require laboratory-scale instruments and facilities that are not practical to bring to the field. Soils have to be carefully processed and standardized (i.e. sieved, homogenized, dried and finely ground) for the analyses. Second, accurate measurement of soil bulk density (i.e. mass per unit soil volume) requires a known volume of soil to be weighed under standard oven-dry moisture conditions, necessitating soil collection from the field. The collection, transportation and processing of soil add considerable time and costs to the operation.

There is active research, ongoing for many years, to reduce the need for destructive sampling and laboratory-based soil processing and combustion-based analysis. Various spectroscopic techniques, such as near- and mid-infrared spectroscopy (NIRS and MIRS, respectively), which measure how soils interact with light radiation of various wavelengths, can yield information on SOC content as well as other chemical and physical properties of the soil [51]. Since the instrumentation consists of a light source and detectors, much faster throughput of samples is possible compared to wet or dry combustion methods. Also, analysis costs are much cheaper and the smaller, less demanding equipment can potentially be deployed in field labs and in developing countries [52]. However, results from spectroscopic methods must be carefully calibrated for different geographic areas and soil types using dry combustion methods as a reference. Various other non-conventional technologies (e.g. laser-induced breakdown spectroscopy, LIBS; diffuse reflectance Fourier transform infrared spectroscopy, DRIFTS; inelastic neutron scattering, INS) have been tested [53] but none has yet emerged as a viable replacement for conventional analysis methods. The most ambitious technological goals are to develop spectroscopic methods that can be used as 'on-the-go sensors', that can be drawn through the soil by tractors or dedicated sampling vehicles to continuously map soil C concentrations [54]. However, such technologies are still at an early stage of development and their utility for quantification in support of soil C offset projects has yet to be determined. Moreoever, these spectroscopic-based estimates of SOC concentrations still require appropriate calibration curves (most likely from conventional destructive sampling) and measures of soil bulk density in order to calculate SOC stocks.

Model-based estimates of soil C stock changes

Models provide a means to predict SOC stock changes, taking into account the integrated effects of different management practices, as well as impacts of varying soil and climate conditions. Mathematical models may be stochastic or deterministic, and some are designed to represent and amalgamate the underlying processes contributing to terrestrial carbon cycling, while others consist of empirical relationships. Models are, of course, an embodiment of theory, experiments and measurement, and particularly for models of soil C dynamics, measurements from long-term field experiments are a primary source of the information upon which these models are based [55].

Take Home messages:

- Both empirical (statistical) and process-based models are widely used to predict/estimate soil C stocks as a function of environmental and management variables.
- Process-based models have potential for a broader range of applicability across gradients of soil, climate and management conditions, but are more complex and difficult to use than empirically based models.
- Model-based quantification systems, if supported by robust, distributed measurement and monitoring networks, have the capability to improve the cost-effectiveness and standardization of estimates of soil C stock change.

Broadly speaking, there are two types of models used to predict SOC stock changes: empirical models, which are based on statistical relationships estimated directly from sets of field experiment observations; and process-based models, in which the model algorithms are based on more general scientific understanding, derived from laboratory- and field-based experiments, as well as a variety of field-based observations of SOC distribution along climatic, vegetation, topographic and geological gradients. Most process-based models aim to achieve a more *general* understanding and predictive capacity, based on the biogeochemical processes that control SOC dynamics and the impacts and interactions of management and environmental factors on those processes. Empirical models are, by definition, restricted to making inferences within the range of conditions represented by the observations used to build the model, whereas process-based models are (in theory at least) more suitable for extrapolation and representation of conditions that might not be well represented in the observational data.

Empirical models

The most well-used and widely known empirical-based model for predicting SOC stock changes is the model developed for the IIPCC national GHG inventory guidelines. The so-called Tier 1 method was developed to provide an easy way for countries (especially developing countries) to estimate national-scale SOC stock changes as a function of changes in land-use and management practices [41,56]. The model uses a broad classification of climate and soil types to derive reference SOC stocks for native ('unmanaged') ecosystems, based on many thousands of measured soil pedons [5]. Then, a set of scaling factors, estimated from statistical estimates of extensive field data sets [57,58], are applied to represent management impacts on stocks (i.e. land-use type, relative C input level, soil management). SOC stock changes are then computed for the stratified (i.e. climate × soil × management) land area being considered, as a function of observed land-use and management changes over a given time period. The model for mineral soil C stock change is given by:

$$\Delta SC = \left(SC_0 - SC_{(0-T)}\right)/D \quad (1a)$$

$$SC_i = SC_R * F_{LU} * F_{MG} * F_I * A \quad (1b)$$

where:

ΔSC = annual soil carbon stock change, Mg C yr^{-1};

SC_0 = soil organic carbon stock at time 0, Mg C ha^{-1};

$SC_{(0\text{-}T)}$ = soil organic carbon stock at time t = 20 years, Mg C ha^{-1};

A = land area of each parcel, ha;

SC_R = the reference carbon stock, Mg C ha^{-1};

F_{LU} = stock change factor for land-use type (dimensionless);

F_{MG} = stock change factor for management/disturbance regime (dimensionless);

F_I = stock change factor for carbon input level (dimensionless);

D = Time dependence of stock change factors, which is the default time period for transition between equilibrium SOC values (in years). The default is 20 years but it depends on assumptions made in computing the factors F_{LU}, F_{MG} and F_I. If T exceeds D, the value for T is used to obtain an annual rate of change over the inventory time period (0–T years).

Constraints for the IPCC method include the lack of field experiment data for many climates, soil types and management combinations. The very broad climate, soil and management classes (and consequently the high degree of aggregation of global data sets) from which the model was developed were intended to support national-scale inventory and reporting. For use in more local application such as for C offset projects, additional data from regional and local field studies would be needed to re-estimate model parameters.

Process-based models

Process-based models generally take the form of computer simulation models that employ sets of differential equations to describe the time and space dynamics of SOM. Most of the models that are currently used to support GHG inventory and/or project-scale quantification were originally developed for research purposes, to analyze the behavior of SOM as a function of environmental and edaphic variables (e.g. temperature, moisture, pH, aeration, soil texture) and land-use and management practices (e.g. vegetation type and productivity, crop rotation, tillage, nutrient management, irrigation, residue management). These types of models attempt to integrate these various factors, and knowledge about the intrinsic controls on decomposition and organic matter stabilization, into generalized models of SOC (and often soil nitrogen) dynamics. This comprehensive approach makes process-based models attractive as predictive tools to support SOC quantification at multiple scales.

Examples of widely used process-based models that simulate SOC dynamics are shown in Table 1. The table includes references to specific instances of site- and landscape-level testing as well as model intercomparisons. Some of these models include additional capabilities to simulate changes in non-CO_2 GHG emissions associated with changes in land management (e.g. DayCent, DNDC).

While process-based models are still used primarily to support basic research, they are increasingly being utilized at local to national scales for soil C and soil GHG inventory purposes. For example, the RothC soil C model is used to estimate soil C stock changes as a component of the

Table 1. **Some widely used process-based models that include soil carbon, providing examples of their application at different scales and in model inter-comparisons. NA denotes instances where articles were not found for the category of application.**

Model	Website	Key reference – model development	Model testing/ application at site scale	Model application at regional scale	Multi-model evaluation	Multi-model application at regional scale
DNDC	http://www.dndc.sr.unh.edu/	Li et al. (1992) [107]	Li et al. (1997) [108]	Grant et al. (2004) [59]	Smith et al. (1997) [109]	Wattenbach et al. (2010) [60]
ROTHC†	http://www.rothamsted.ac.uk/sustainable-soils-and-grassland-systems/rothamsted-carbon-model-rothc	Jenkinson (1990) [61]	Coleman et al. (1997) [110]	Cerri et al. (2007) [111]	Smith et al. (1997) [109]	Falloon and Smith (2002) [62]
APSIM	www.apsim.info	Mccown et al. (1995) [63]	Luo et al. (2011) [112]	O'Leary et al. (2016) [64]	Moore et al. (2014) [65], Basso et al. (2018) [98]	NA
DAYCENT	http://www.nrel.colostate.edu/projects/daycent/	Del Grosso et al. (2001) [66]	Del Grosso et al. (2008) [113]	Nocentini et al. (2015) [67]	Del Grosso et al. (2016) [114], Basso et al. (2018) [98]	Smith et al. (2012) [96]
DSSAT	http://www.dssat.net	Jones et al. (2003) [68]	Gijsman et al. (2002) [69]	De Sanctis (2012) [70]	Yang et al. (2013) [71]	NA
ECOSYS	http://ecosys.ualberta.ca/	Grant (1997) [72]	Grant et al. (2001) [73]	Mekonnen et al. (2016) [74]	Lokupitiya et al. (2016) [75], Basso et al. (2018) [98]	NA
EPIC	http://epicapex.tamu.edu/	Izaurralde et al. (2006) [115]	Apezteguia et al. (2009) [76]	Zhang et al. (2015) [77]	Lokupitiya et al. (2016) [75]	NA
SOCRATES	http://socrates.n2o.net.au/main	Grace et al. (2006a) [78]	Grace et al. (2006b) [79]	NA	Izaurralde et al. (2001) [116]	NA

†For soil C inventory applications, the ROTHC model soil C model can be imbedded within a full ecosystem-scale model framework, such as FullCAM [67] which is used for soil C accounting purposes in Australia.

Full-CAM national GHG inventory system [58], and the DayCent model is used for soil C stocks changes and soil emissions of N_2O and CH_4 in the US national GHG inventory and reporting system [81].

Most model-based decision support systems (DSSs) for soil C estimation employ empirical models, often derived from the IPCC Tier 1 method described above [82], although COMET-Farm, a web-based full GHG accounting DSS, employs both empirical models for some GHG emission sources as well as the dynamic process-based DayCent model for estimates of soil C stock changes and soil N_2O emissions [83]. Combining biogeochemical process models, global positioning system (GPS) sensors and financial calculators can further elaborate decision-support systems for the fine spatial scales employed in precision agriculture [84].

To further develop the capabilities of process-based models for soil C accounting purposes, it will be essential to better integrate models with supporting measurements [55], for example from networks of soil C monitoring sites [85], flux measurement networks and existing long-term field experiments [86]. Continued efforts are needed to extend and evaluate the capabilities of process-based models to predict soil C changes and GHG emissions, to provide full-cost accounting in GHG offset projects and, when possible, to compare performance in model intercomparison experiments [87].

Case studies of soil C quantification for GHG offsets

Soil carbon accounting systems are gaining momentum in several developed countries that are including agricultural GHG offset options as part of their mitigation portfolios. Three examples of soil C accounting systems that have been developed to support agricultural soil C offset projects are those implemented by the national government of Australia and the provincial governments of both Alberta and Saskatchewan (Canada). These three systems are presented as case studies that illustrate the diverse ways in which information from field measurement and monitoring systems can be combined with model-based quantification systems to support programs that promote SOC sequestration and improve function of managed soils. These examples focus on the quantification methods, and other issues associated with offset protocols such as additionality, leakage and permanence are not discussed in detail.

Australia

The Australian government has established the Emissions Reduction Fund (ERF) to encourage the adoption of management strategies that result in either the reduction of GHG emissions or the sequestration of atmospheric CO_2. The ERF is enacted through the Carbon Credits (Carbon Farming Initiative) Act 2011 (CFI). Under the ERF,

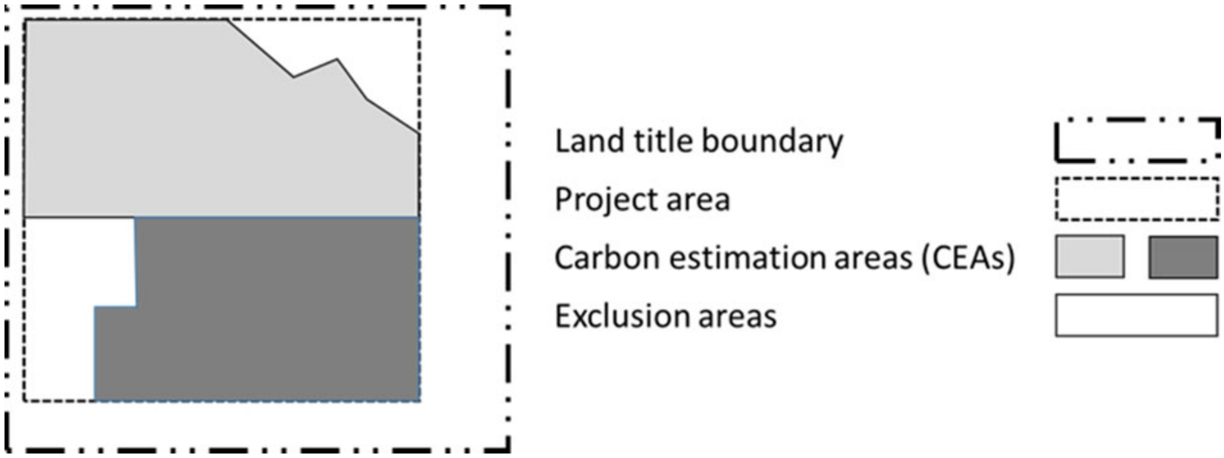

Figure 1. Schematic representation of the relationship among land title boundary, project area and carbon estimation areas. Source: Author

Table 2. Default values for soil carbon sequestration defined for each of the three project types for carbon payments in Australia.

	Sequestration value (t CO_2-e ha^{-1} $year^{-1}$)		
Project type	Marginal benefit	Some benefit	More benefit
Sustainable intensification	0.11	0.59	1.65
Stubble retention	0.07	0.29	0.73
Conversion to pasture	0.22	0.44	0.84

businesses, farmers and community groups can earn C credits by undertaking projects to reduce emissions or sequester carbon. A range of mitigation activities have been approved for all sectors of the economy; here, the focus is on activities that increase SOC stocks. Projects must comply with the Offsets Integrity Standards, which ensure that any emission reductions, in this case sequestered carbon, are additional, measureable and verifiable, eligible, evidence-based, material and conservative. Once approved and implemented, the methods can be used to generate Australian Carbon Credit Units (ACCUs). One ACCU equates to an emission avoidance or sequestration of 1 tonne of carbon dioxide equivalent (CO_2-e) and can be sold to the Australian government or in a secondary market to generate income.

Initially, two methods for quantifying soil C sequestration were endorsed by the Emissions Reduction Assurance Committee and adopted by the Minister for the Environment and Energy: 'Sequestering carbon in soils in grazing systems' and 'Estimating sequestration of C in soil using default values'. The first method was based on direct measurement of changes in SOC stocks obtained through sampling and analysis over time, whereas the second method was based on the use of default rates of soil C change predicted using the FullCAM process-based model that was designed to be nationally applicable [88,89]. Common to both soil C methods are the definitions of a project, a project area and carbon estimation areas (CEAs) (Figure 1).

'Sequestering C in soils in grazing systems' was the first soil C quantification method developed for use in the ERF. It was designed to quantify the magnitude and certainty of soil C change within CEAs of any size. Under this method, a project proponent measures baseline soil C stocks to a minimum depth of 30 cm, implements new management activities that would not have occurred under a business-as-usual condition and measures future soil C stocks at nominated intervals through time.

The second soil C quantification method, 'Estimating carbon sequestration in soil with default values', offers three project types that can receive ACCUs: sustainable intensification, stubble retention and conversion to pastures. Eligible lands and associated default rates of soil C sequestration associated with each project type were defined using an updated version of the FullCAM model and its associated data tables that were used to prepare Australia's 2015 submission to the UNFCCC [88]. The RothC soil carbon model (Table 1) is a submodel contained within the broader scope of the FullCAM system model.

For the model-based method, there are three defined classes of soil C sequestration rates: marginal benefit, some benefit and more benefit. These rates were determined by a series of simulations and statistical tests to generate a histogram, enabling the three-class regionalization (Table 2; Figure 2). Provided a project meets its reporting obligations and remains eligible, the amount of C sequestered is defined by multiplying the duration of the project by the respective rate of carbon sequestration provided in Table 2. More information on allowable activities and conditions can

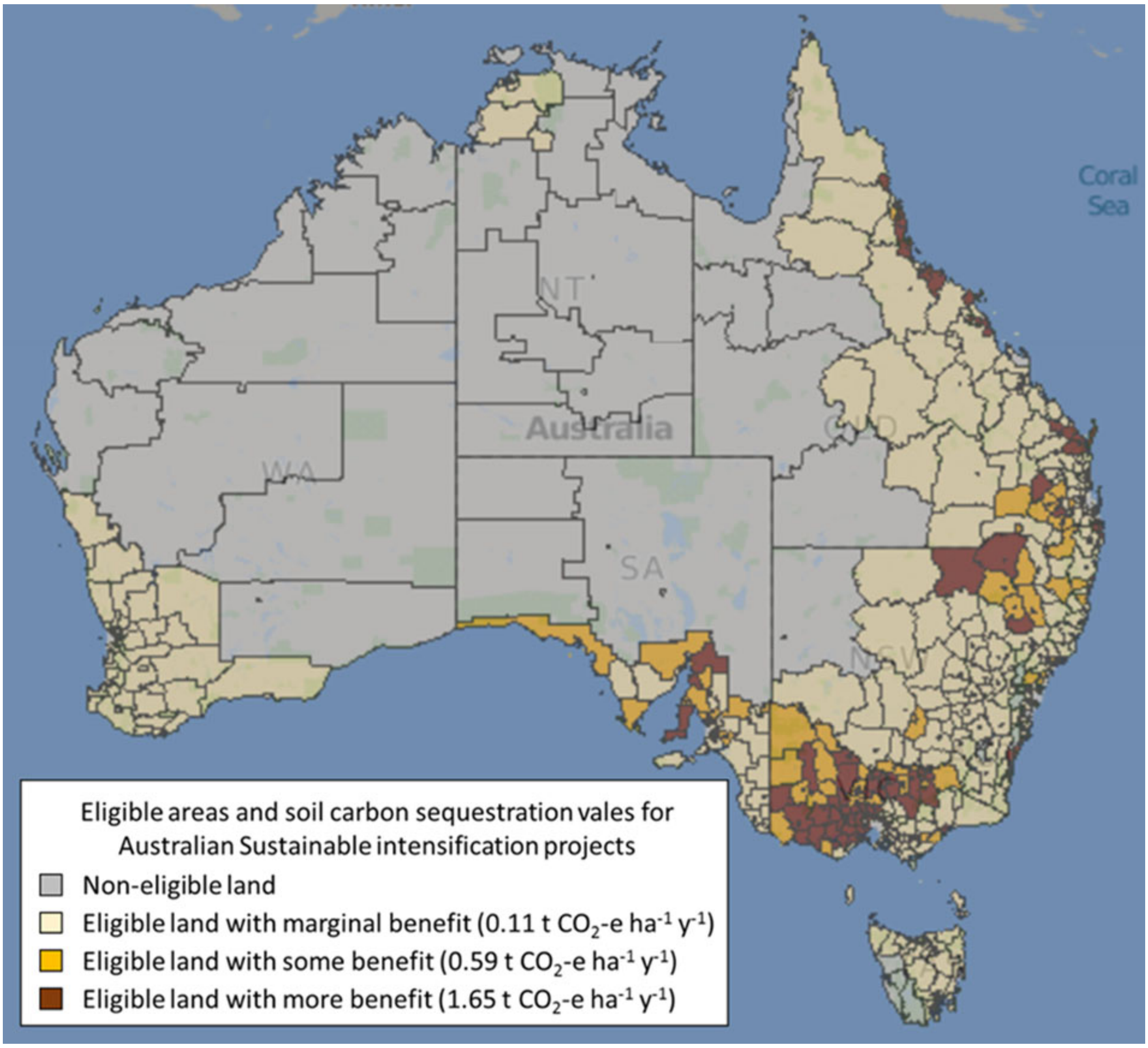

Figure 2. Delineation of eligible and non-eligible lands for sustainable intensification projects, and the areas associated with each of the three levels of soil C sequestration benefit predicted using the soil carbon component of the FullCAM simulation model. Source: Author

be found at www.environment.gov.au/climate-change/emissions-reduction-fund/methods/sequestration-carbon-modelled-abatement-estimates.

For the direct measurement approach, uncertainty associated with measured soil C stock change was addressed in two ways. First, statistical approaches were used to define the level of carbon sequestration associated with a probability of exceedance equal to 60%. This approach applied a discount to measured values, with the size of the discount being linked to the variance of measured soil carbon stock values. Additionally, to help insure against initial over-crediting until such time as a long-term trend is established, credits for any carbon sequestered between the baseline measurement and the first temporal measurement were reduced by 50%. As the number of temporal measurements increased, the potential for spatial and environmental variations to impact the derivation of carbon sequestration values diminished and a regression approach was applied in an attempt to move toward the 'true' temporal trend of soil carbon stock change associated with the applied management practices.

For the emission factor approach, the uncertainty associated with activity data and the model was determined using a Monte Carlo analysis in conjunction with the IPCC 'Approach 1' propagation of error method as described in the IPCC inventory guidelines [41] and reported in the Australian Government Submission to the UNFCCC (http://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications/national-inventory-report-2016). For the emissions factors themselves, statistical analysis applied to the derived data enabled a three-class regionalization of the scenarios.

Implementing a soil carbon sequestration project using either of the methods described above may alter emissions of methane (CH_4) and/or

Table 3. Greenhouse gases required to be included in net abatement calculations for the various potential agricultural management activities that can be implemented in carbon sequestration projects in Australia.

Carbon pool or emission source	Greenhouse gas	Include/exclude	Justification and process for inclusion
Soil organic carbon	CO_2	Include (contained within the default sequestration values)	This is the primary emission sink associated with soil carbon sequestration projects.
Livestock	N_2O CH_4	Include	Emissions associated with enteric fermentation, dung and urine change with increases or decreases in stocking rates. Impacts of feed quality are excluded. National Greenhouse Gas Inventory emission factors are to be used.
Synthetic fertilizer	CO_2 N_2O	Include	Application of synthetic nitrogen fertilizers result in emissions of N_2O, and in the case of urea also CO_2. National Greenhouse Gas Inventory (NGGI) emission factors are to be used.
Non-synthetic organic-based fertilizers	CO_2 N_2O CH_4	Exclude	Non-synthetic fertilizers are derived from waste streams. No additional emissions are required to be accounted for since emissions from within a Carbon Estimation Area (CEA) to which they have been applied would be no greater than what would have occurred had the materials not been applied.
Agricultural lime	CO_2	Include	Application of agriculture lime has the potential to emit CO_2 as carbonates react with the soil to neutralize acidity. National Greenhouse Gas Inventory emission factors are to be used.
Irrigation energy	CO_2 N_2O CH_4	Include	Irrigating previously non-irrigated areas may involve an increase in emissions due to the consumption of diesel fuel or electricity and must be accounted for. NGGI emission factors are to be used.
Residues – decomposition	N_2O	Include	Retention of residues fromcrops will result in the emission of N_2O when they decompose. NGGI emission factors are to be used.
Residues – burning	CO_2 N_2O CH_4	Exclude CO_2 Include N_2O and CH_4	Any changes in the quantity of residue carbon not going to CO_2 will be reflected in the sequestered carbon within the soil. Net changes in N_2O and CH_4 emissions due to the removal of burning in progressing from the baseline to project conditions need to be accounted for. National Inventory Report emission factors are to be used.

nitrous oxide (N_2O) (Table 3). Changes in CH_4 and N_2O emissions must be taken into account in addition to the amount of C sequestered to derive the total net abatement provided by a project. For each of the management activities eligible under the two methods, the net abatement is calculated by considering each of the gases identified in Table 3. The calculations for emissions incurred as a result of undertaking the carbon sequestration activities are consistent with those applied in the Australian National Greenhouse Accounts.

The 2015–2016 method prioritization process resulted in an agreement that a new soil carbon method should be developed, building on the two existing soil carbon methodologies. The need was identified because there had been limited uptake of the existing soil carbon methods. This outcome was attributed to the narrow range of farming systems that were able to participate and the high costs of direct measurement. The Carbon Credits (Carbon Farming Initiative – Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018 seeks to overcome these limitations by introducing new components and adapting some components from the two earlier soil carbon methods. This provides proponents with the flexibility to respond to market forces, participate in the Emission Reduction Fund and continue to make land-management decisions enabling them to meet their broader business objectives.

Alberta, Canada

In 2007, the Government of Alberta became the first jurisdiction to enable agriculture offsets with an amendment of the Climate Change and Emissions Management Act (CCEMA) to require industrial facilities with emissions exceeding 100,000 tonnes per year of GHGs (CO_2-e) to report and reduce their emissions to established targets. Under the CCEMA, large industrial emitters are required to reduce their emissions by 12% below their baseline. They could pick any of three options to meet their reduction goal: emission performance credits, technology fund credits or emission offsets.

The Alberta Offset System operates under an extensive set of policies, rules and standards (Offset Quantification Protocols and Guidance Documents). to ensure that offsets are of the highest rigor and quality to meet regulated companies' requirements. The development process for protocols includes expert engagement, defensible scientific methodologies, a rigorous peer-review process, and documented transparency. A range of

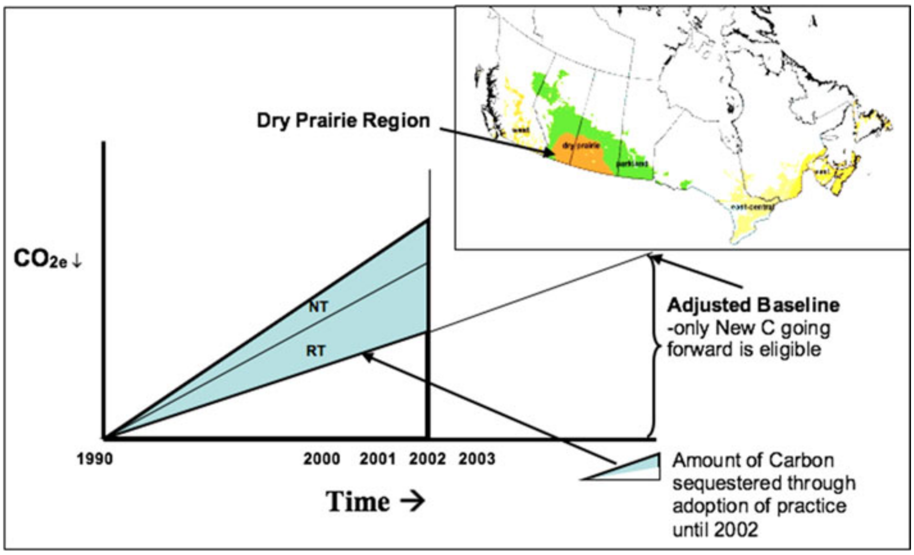

Figure 3. **Schematic of the adjusted regional baseline for the Dry Prairie Region – discount based on the adoption rate of reduced till (RT) and no-till (NT) practice for the baseline year (2002). Source: Author**

science-based quantification protocols were developed transparently with a technical review to help provide certainty to buyers and sellers and reduce transaction costs. All verified tonnes are serialized and are listed on a registry with oversight by the Canadian Standards Association.

The Alberta market also relies on aggregator companies, which aggregate credits from a number of sources (a group of farmers or land holders) to assemble projects large enough to interest buyers. NGOs and aggregators play a pivotal role in reducing transaction costs so that individual farms can participate in the carbon market and generate revenues. Aggregators ensure all participants adhere to the protocol terms and conditions and arrange for third-party verification of the assembled project. All aggregation and verification costs are borne by the carbon offset project developer.

The Conservation Cropping Protocol (CCP) is a 2012 revision and upgrade of the previous Tillage System Management Protocol. This protocol focuses on sequestration of additional SOC attributable to a change from conventional to no-till annual cropping practices or for reduction in summer fallow. It has been the most sought-after type of agricultural GHG project, and conservation tillage offsets have made up roughly 30% or more of the annual market share, delivering over 1.5 million tonnes of offsets since 2007.

The protocol uses Canada's National Emissions Tier II methodology, which developed soil C sequestration coefficients based on measuring and modeling local crop rotations, soil/landscape types and inter-annual climate variation for geo-specific polygons in the national eco-stratification system. This empirical model approach uses sequestration coefficients to provide a low-range estimate of increased SOC stocks that might be expected from a change from conventional to no-till practices. It presents a simplified way of estimating SOC increases based on a verified change in management practice, without direct measurement by soil sampling and analysis. Alberta's GHG regulations require that all GHGs must be considered (aggregate net CO_2-e mass). Modeling is the most efficient and cost-effective method for accounting for all GHG changes over large, diverse areas. The modeling tools are the same as those for national inventory work and are anchored with verification work using research plot data.

Eligible actions for offsets typically must be new and additional to business as usual. Since reduced tillage and no-tillage practices were already being adopted in western Canada, this proved particularly challenging. The solution was to develop a 'moving baseline' to accommodate early adopters as well as late adopters of the practice. The sequestration coefficient was discounted according to the observed rate of increase in the adoption of no-till and reduced till practices as accounted for by the national agriculture census taken every 5 years. To satisfy additionality, the quantification uses a discounted or 'adjusted baseline' to subtract out carbon accrued before the 2002 start year of the offset eligibility criteria from the more recent adoption rates of zero tillage from a region – deriving regional discounted baselines. In this manner, only the additional or incremental soil C resulting from the continuation of the practice post 2002 can count as an offset credit. Thus, the adjusted baseline is only applied to activities that sequester C on a go-forward basis (Figure 3). Thus, all tillage management projects get a 'haircut' off their carbon tonnes, but early adopters are allowed to participate to maintain the practice, and late adopters get a smaller coefficient for their C storage to satisfy additionality requirements with the adjusted baseline.

The validity of sequestered soil carbon for no-till projects in Alberta is ensured by a government-backed policy approach known as an 'assurance factor', which is applied to every tonne of carbon offset created under the protocol. Each coefficient is discounted by a percentage for the risk of management practice reversal derived for specific regions in Alberta. This fraction of the credit is set aside by the government (e.g. 10% discount on every verified tonne), resulting in 0.1 t CO_2-e collected by the government for each verified tonne. This reserve is held back to protect against soil carbon lost to the atmosphere if conventional tillage practices are resumed in the future; the reserve is operationalized through government policy.

Regardless of how good the scientific basis is, a protocol can fail for a variety of other reasons including escalating transaction and verification costs. Governments focus on science-based systems and often do not consider transaction or implementation costs when designing offset markets. To minimize risks and keep transaction costs from escalating, Alberta Agriculture and Forestry [90] has created and maintained a website to help inform industry stakeholders of rules and guidance materials for the sector. Another burden that sometimes goes unseen is the cost of verification, which does not align with discrete records of financial transactions or recording meters on factory smokestacks. Non-metered biologic systems do not conform easily to existing audit paths and expectations. Similar to designing a project with the end in mind, offset design should keep in mind the verification needs and associated costs in order to maximize revenues to the sources of project tonnes.

What do participating farmers think of all this after a decade? In late 2017 a producer survey was conducted by Team Alberta, a consortium of the wheat, canola, barley and pulse crop commodity organizations. A private survey firm pre-certified respondents with a telephone call to verify they were not a hobby or niche market farm and that they produced annual crops. A follow-up online survey questioned 339 respondents on several topics, one of which was the CCP.

Just over one third of respondents had participated in the CCP, and this proportion increased to almost half of the larger acreage respondents. Nearly three quarters of respondents were either 'satisfied' or 'somewhat satisfied'. The top three improvements suggested were better compensation for their time and effort, simplified program forms and paperwork, and a wider range of available practices.

The compliance cost for mandatory GHG reductions in Alberta was CAD$15/tonne from 2007 to 2015. As of 2018 it became an economy-wide pricing of CAD$30/tonne and is scheduled to move to CAD$50 by 2022 in alignment with new federal legislation, the Pan Canadian Framework on Clean Growth and Climate Change. The higher pricing with no expected increase in transaction costs should make offsets more practical and more attractive to agricultural producers.

A decade of experience plus new policy signals and price changes will enable agriculture to continue in a regulated GHG market and perhaps participate in more pragmatic voluntary offset markets as well as programmatic and sustainability markets for a range of industries and governments. Scientific support and evidence will be needed to fill gaps and provide assurance for future protocols and delivery models.

Saskatchewan, Canada

The Prairie Soil Carbon Balance (PSCB) project was a broad-scale feasibility assessment of direct measurement of changes in soil C stocks in response to a shift from conventional tillage to no-till, direct-seeded cropping systems in Saskatchewan [91]. Although not designed to monetize soil carbon offsets, the PSCB project was partially funded by farm organizations with an interest in securing financial recognition for GHG mitigation. In 1996, a network of 137 benchmark sites was established on commercial farm fields where a shift from conventional to no-till and direct seeding had occurred (in 1996 or 1997; Figure 4). The soil sampling and analysis strategy utilized a benchmark site approach designed for precision periodic resampling as outlined by Ellert, Janzen, and McConkey [92]. At each sampling time, six cores 7 cm in diameter were collected to a depth of 40 cm (sectioned into 10-cm depth increments). In addition to the project establishment year in 1996, soils were collected again in 1999, 2005 and 2011.

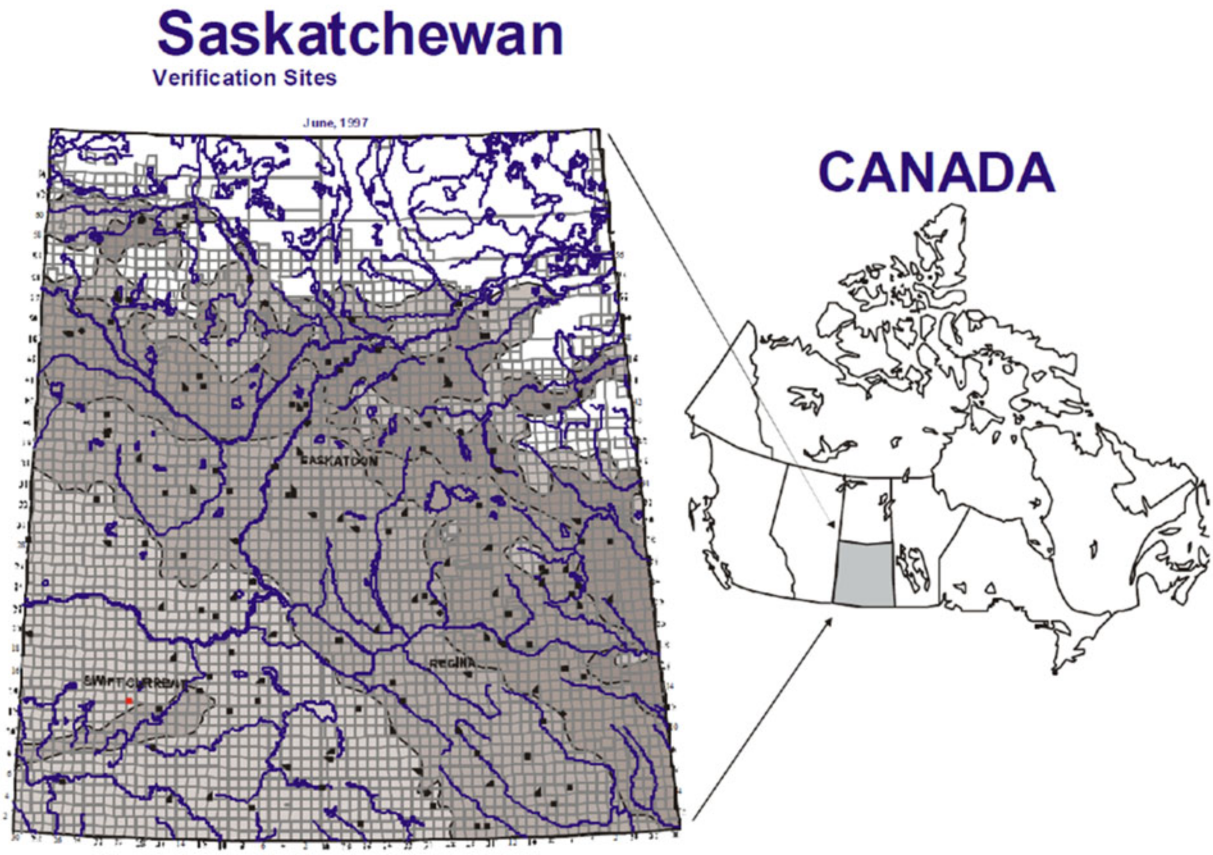

Figure 4. **Locations of 137 sites established in 1996 to assess soil organic carbon change in the Prairie Soil Carbon Balance (PSCB) project. The background map depicts the major soil zones of Saskatchewan. Source: Author**

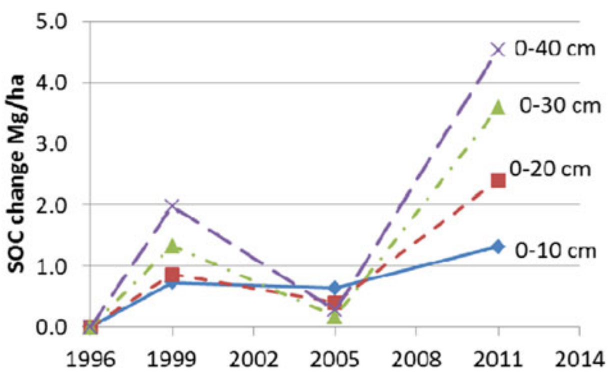

Figure 5. **Changes in soil organic carbon (SOC) after adoption of no-till in 1996 (n = 80 sites available in 2011 plotted for all sampling years; 95% confidence interval typically was ± 1.5 for the 30 and 40 cm depths; ± 0.5 in 1996; adapted from [70]).**

This 15-year study illustrates some of the logistical challenges of direct sampling of SOC through time. During the study, there were numerous changes in ownership or land management at the study sites and some sites were lost to attrition. In 2005, 121 of the original 137 sites were sampled, and at the last sampling in 2011, only 82 sites had the required management data and manager authorization for inclusion in the project. Additionally, because of the heterogeneity of SOC within fields (30–65 ha), it was prohibitively expensive to collect enough samples to estimate the average stock across the field.

Despite these challenges, this project yielded valuable insights into SOC dynamics. Grouping of the benchmark sites among contrasting fields provided interpretable estimates of temporal changes in SOC stocks associated with adoption of no-till, direct-seeding practices (Figure 5). The temporal changes varied among sampling intervals, and in 2005 soil C stock changes following no-till adoption were not significantly different from zero, possibly because the 2001–2003 drought reduced C inputs to a greater extent than decomposition did. However, by the 2011 sampling, SOC stocks had rebounded, and the gains in soil C attributable to no-till adoption increased with the cumulative depth or soil mass considered (Figure 5). This was contrary to the expectation that a majority of soil C accumulated under no-till would reside in the surface soil layers. Averaged over the 15-year study, no-till practices increased soil C stocks in the 0–30 cm layer by about 0.23 Mg C ha^{-1} yr^{-1}. The PSCB project indicated that increases in soil C stocks in response to the adoption of no-till practices were measurable, but estimates were best made in aggregate for 25 or more microsites distributed across several fields; otherwise, measurement costs for individual fields became prohibitive.

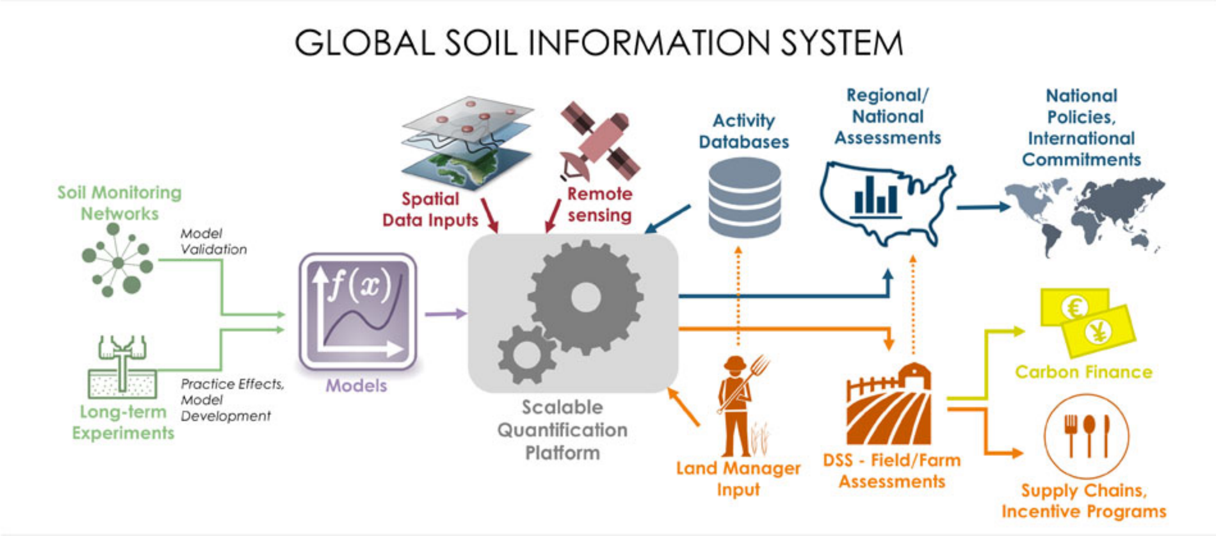

Figure 6. Overview of the components and information flow for an approach to quantify soil carbon stock changes (and net GHG emissions) from field to national scales, purposed to support different implementation policies to remove atmospheric CO_2 and sequester soil carbon. Modified from [15]. DSS: Decision support system.

Toward a new global soil information system

There has been substantial progress toward achieving a broader appreciation (e.g. among policymakers, environmental groups and the general public) of the key role of SOC in relation to core ecosystem services from working lands. The science is also advancing, with improved understanding of fundamental mechanisms controlling SOC dynamics as well as in measuring and modeling changes in SOC pools in response to both environmental and management factors. As a result of this progress, entrepreneurial programs and methods are being developed that can help lead the way toward a greater inclusion of soil carbon management in farmers' and ranchers' decision-making going forward.

However, to move toward an aggressive implementation of best land-use and management practices to promote soil health globally and to incentivize CO_2 removal and sequestration in soils at gigatonne-per-year scales [15,17,93], a new soil information system, with global reach and the capacity to evolve as the science advances, is needed (Figure 6).

While much of the data and many of the tools, technologies and collaborations needed already exist [85,94,95], the information is often fragmented and data availability is often limited [96]. More coordination, greater transparency and easier accessibility to the tools and data, among and between field scientists, remote sensing specialists, modelers and land managers, is needed.

Figure 6 depicts a virtual data-model quantification platform that could form the core of a new soil information system. Starting on the left-hand side of the diagram, key data sources to inform and validate SOC estimates are depicted. The utility of data from long-term field experiments to help formulate, parameterize and validate predictive models of soil carbon stock change has long been acknowledged [e.g. 20,97]; expanding the compilation of data from high-quality experiments across the globe, and making the data easily available for modelers and analysts, can accelerate the development and improvement of models [65]. Soil monitoring networks, in which periodic soil measurements are made on actual working lands, have been established in several countries [84] and can play a vital role in reducing model uncertainty [47]. However, such monitoring networks are lacking in most countries, and where the data do exist, they are often not readily available to the research community. Developing data-sharing agreements to combine country-specific SOC monitoring data sets – with appropriate safeguards to protect landowner privacy – could pave the way toward a consolidated global in-field soil monitoring network, the accessibility and utility of which could incentivize other countries to join.

Both research site data and data from distributed soil monitoring networks can feed into dynamic process-based models (such as those listed in Table 1) that predict vegetation and soil carbon dynamics and other ecosystem variables (e.g. water dynamics, GHG fluxes). Such a platform would support and facilitate the use of ensemble modeling approaches. Advantages of an ensemble approach are to provide 'central tendency' estimates from a group of models [98] and to better assess model-associated uncertainty. Ensemble modeling has become standard practice in other fields that depend heavily on model-based predictions, such as weather forecasting and integrated assessment, but has yet to be routinely deployed for soil carbon modeling [95].

Model assemblages are driven by spatially resolved data sets (Figure 6, center) including climatic variables (e.g. temperature, precipitation, solar radiation), edaphic conditions (e.g. soil texture, mineralogy, soil profile depth, topographic features) and land-use and management activity data (e.g. crop rotations, tillage, nutrient management). Provided that the models employed are generalizable over a sufficiently broad range of environmental conditions, the scale of inference for predicted variables (e.g. ΔSOC) is largely determined by the spatial resolution of the data inputs. While high-resolution soil maps and fine-scale gridded weather data sets exist for a number of countries, they are lacking for much of the tropics, which constrains the capacity to perform local-scale (i.e. sub-km^2) analyses. Continuing efforts to improve global soil mapping [99,100], particularly in the tropics, is imperative, as is making existing high-resolution soil maps (e.g. in Europe) more easily available to the research community [101].

The paucity of fine-scale management activity data (i.e. what is actually happening on the landscape) is a major constraint, even in developed countries with well-funded agricultural survey and census capacities. In the latter case, many survey efforts result in highly aggregated management activity data that have limited utility at local scales. The situation is even more challenging in developing countries lacking the resources for extensive land management and rural economic surveys, where there are almost no comprehensive data sets on management activities. However, a major breakthrough to collect detailed and local-scale management activity data is possible by engaging land users themselves in providing local-scale management activity data via a crowd-sourcing model [102]. Initial efforts using the LandPKS system [103] show promise in not only collecting management activity data but also in mobilizing local knowledge about soil characteristics at the field scale, that could provide inputs to model-based assessment.

Finally, remote sensing (RS) offers the potential to provide low cost, fine-scale and globally available data on land cover and crop species as well as information on crop residue coverage, tillage and irrigation practices, which can both supplement ground-based management activity data sources and/or be used as independent verification of land user-reported management activities. Data acquisition and analysis methods, from both satellite and airborne platforms, have been shown to be feasible for many categories of agricultural management activity data [e.g. 104,105]. However, to date many RS methods to assay agricultural practices are still in a research mode and were often applied to limited test areas and without deployment of multiple sensors [58,106]. Hence, there is a need to test promising methods more widely and then build out RS capabilities that can rapidly and routinely provide data on management practices at high spatial resolution, anywhere on the globe.

Taken collectively, dynamic models, supported by experimental and field-based monitoring data, and driven by spatially distributed soil, climate and management data – both ground-based and from remote sensing – can provide robust and low-cost quantification of soil C stock changes (and non-CO_2 GHG fluxes). A scalable system will be needed, capable of analyses at the country level, to support national policies and international agreements, as well as quantification at farm and landscape scales, to support sustainable supply-chain initiatives and/or carbon finance schemes which can directly incentivize farmers to adopt C-sequestering, soil-building and GHG-reducing practices (Figure 6, right).

The two workshops on which this paper was based, as well as recent papers and other meetings convened by government, industry, individual philanthropists and non-profit organizations, reflect a growing consensus among land managers, soil scientists, government, and technology communities of the need to build a new soil information service. Such a service would fully leverage the technological capacity to capture, curate, share and explore more granular and dynamic data and knowledge resources in a learning, deeply interactive, open system. A new soil information service must have a holistic perspective on current and future needs for land and soil resource information (e.g. across multiple scales and across all managed lands) and be nimble, pluralistic and collaborative. Recognizing that such a bold vision lies beyond the capability of any individual entity, including government, this community holds as a core value that long-term success will only be achieved through the coordinated collaboration of a diverse group of motivated stakeholders across the globe.

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References

1. Powlson DS, Gregory PJ, Whalley WR, et al. Soil management in relation to sustainable agriculture and ecosystem services. Food Policy. 2011;36:S72–S87. doi:10.1016/j.foodpol.2010.11.025.
2. Hopkins DW, Gregorich EG. Managing the soil–plant system for the delivery of ecosystem services. In: Gregory PJ, Nortcliff S. Soil conditions and plant growth. 2013;390–416. Blackwell Publishing Ltd.
3. Oldeman LR, Hakkeling RTA, Sombroek WG. 2017. World map of the status of human-induced soil degradation: an explanatory note. International Soil Reference and Information Centre, Wageningen, Netherlands.
4. Smith P, Lutfalla S, Riley WJ, Torn MS, Schmidt MWI, Soussana J-F. The changing faces of soil organic matter research. Eur J Soil Sci. 2018;69:23–30. doi:10.1111/ejss.12500.
5. Batjes NH. Total carbon and nitrogen in the soils of the world. Eur J Soil Sci. 1996;47:151–163. doi:10.1111/j.1365-2389.1996.tb01386.x.
6. Amundson R, Berhe AA, Hopmans JW, Olson C, Sztein AE, Sparks DL. Soil science. Soil and human security in the 21st century. Science. 2015;348:1261071. doi:10.1126/science.1261071.
7. Lal R. Restoring soil quality to mitigate soil degradation. Sustainability. 2015;7:5875–5895. doi:10.3390/su7055875.
8. Watts CW, Dexter AR. Soil friability: theory, measurement and the effects of management and organic carbon content. Eur J Soil Sci. 1998;49:73–84. doi:10.1046/j.1365-2389.1998.00129.x.
9. Beniston JW, Shipitalo MJ, Lal R, et al. Carbon and macronutrient losses during accelerated erosion under different tillage and residue management. Eur J Soil Sci. 2015;66:218–225. doi:10.1111/ejss.12205.
10. Han X, Xu C, Dungait JAJ, et al. Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: a system analysis. Biogeosciences. 2018;15:1933–1946. doi:10.5194/bg-15-1933-2018.
11. Lal R. Sequestering carbon in soils of agro-ecosystems. Food Policy. 2011;36:S33–S39. doi:10.1016/j.foodpol.2010.12.001.
12. Smith PM, Bustamante H, Ahammad H, et al. Climate Change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al. Forestry and other land use. 2014. IPCC, Geneva, Switzerland
13. Hansen JM, Sato P, Kharecha K, et al. Young people's burden: requirement of negative CO2 emissions. Earth Syst. Dynam. Discuss.4 October 2016:1–40. https://doi.org/10.5194/esd-2016-42.
14. Rockström J, Gaffney O, Rogelj J, et al. A roadmap for rapid decarbonization. Science. 2017;355:1269–1271. doi:10.1126/science.aah3443.
15. NASEM (National Academies of Sciences, Engineering, and Medicine). Negative emissions technologies and reliable sequestration: a research agenda. Washington, DC: The National Academies Press; 2018. doi: https://doi.org/10.17226/25259.
16. Zhao Y, Wang M, Hu S, et al. Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. Proc Natl Acad Sci USA. 2018;115:4045–4050. doi:10.1073/pnas.1700292114.
17. Paustian K, Lehmann J, Ogle S, et al. Climate-smart soils. Nature. 2016;532:49–57. doi:10.1038/nature17174.
18. Barnwell TO, Jackson RB, Elliott ET, et al. An approach to assessment of management impacts on agricultural soil carbon. Water Air Soil Pollut. 1992;64:423–435. doi:10.1007/BF00477114.

19. Paul EAK, Paustian K, Elliott ET, and Cole CV. Soil organic matter in temperate agroecosystems: Long-term experiments in North America. Am J Altern Agric. 2000;15:43–43. https://doi.org/10.1017/S0889189300008456.
20. Powlson DS. Why evaluate soil organic matter models? In: Powlson, DS, Smith, P, and Smith, J.U., editors. Evaluation of soil organic matter models. Berlin (Germany): Springer; 1996. p. 3–11. https://doi.org/10.1007/978-3-642-61094-3_1.
21. Paustian K. Modelling soil biology and biochemical processes for sustainable agriculture research. In: Pankhurst C, Doube BM, Gupta VVSR, and Grace PR, editors. Management of Soil Biota in sustainable farming systems. Melbourne (VIC): CSIRO Publ.; 1994. p. 182–196.
22. Schmidt MWI, Torn MS, Abiven S, et al. Persistence of soil organic matter as an ecosystem property. Nature. 2011;478:49–56. doi:10.1038/nature10386.
23. Dungait JAJ, Hopkins DW, Gregory AS, et al. Soil organic matter turnover is governed by accessibility not recalcitrance. Glob Change Biol. 2012;18:1781–1796. doi:10.1111/j.1365-2486.2012.02665.x.
24. Lehman RM, Cambardella CA, Stott DE, et al. Understanding and enhancing soil biological health: the solution for reversing soil degradation. Sustainability. 2015;7:988–1027. doi:10.3390/su7010988.
25. Boyer CN, Lambert DM, Larson JA, et al. Investment analysis of cover crop and no-tillage systems on Tennessee cotton. Agron J. 2018;110:331–338. doi:10.2134/agronj2017.08.0431.
26. Poffenbarger H, Artz G, Dahlke G, et al. An economic analysis of integrated crop-livestock systems in Iowa, U.S.A. Agric Syst. 2017;157:51–69. doi:10.1016/j.agsy.2017.07.001.
27. Hunt ND, Hill JD, Liebman M. Reducing freshwater toxicity while maintaining weed control, profits, and productivity: effects of increased crop rotation diversity and reduced herbicide Usage. Environ Sci Technol. 2017;51:1707–1717. doi:10.1021/acs.est.6b04086.
28. Chambers A, Lal R, Paustian K. Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per thousand initiative. J. Soil Water Conserv. 2016;71:68A–74A. doi:10.2489/jswc.71.3.68A.
29. Steele R, Hatfield JL. Navigating climate-related challenges on working lands: a special issue by the USDA climate hubs and their partners. Clim Change. 2018;146:1–3. doi:10.1007/s10584-017-2129-3.
30. Bryant L, O'Connor C. Creating incentives to improve soil health through the federal crop insurance program. In Field, DS, Morgan, CLS, McBratney, AB, editors. Global soil security. Springer; Switzerland. 2017. p. 403–409.
31. Borrelli P, Paustian K, Panagos P, Jones A, Schutt B, Lugato E. Effect of good agricultural and environmental conditions on erosion and soil organic carbon balance: a national case study. Land Use Policy. 2016;50:408–421. doi:10.1016/j.landusepol.2015.09.033.
32. Hamrick K, Goldstein A. Raising ambition—State of the voluntary carbon markets 2016. Washington (DC): Forest Trends' Ecosystem Marketplace. http://www.forest-trends.org/documents/files/doc_5242.pdf.
33. Govaerts B, Verhulst N, Castellanos-Navarrete A, et al. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit Rev Plant Sci. 2009;28:97–122. doi:10.1080/07352680902776358.
34. Baldocchi DD. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Glob Change Biol. 2003;9:479–492. doi:10.1046/j.1365-2486.2003.00629.x.
35. Ammann C, Flechard CR, Leifeld J, et al. The carbon budget of newly established temperate grassland depends on management intensity. Agric Ecosyst Environ Greenhouse Gas Balance Grasslands Eur. 2007;121:5–20. doi:10.1016/j.agee.2006.12.002.
36. Matsuura S, Miyata A, Mano M, et al. Seasonal carbon dynamics and the effects of manure application on carbon budget of a managed grassland in a temperate, humid region in Japan. Grassl Sci. 2014. 60: 69-129. doi:10.1111/grs.12042.
37. Hirano T, Segah H, Harada T, et al. Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. Glob Change Biol. 2007;13:412–425. doi:10.1111/j.1365-2486.2006.01301.x.
38. Nieveen JP, Campbell DI, Schipper LA, et al. Carbon exchange of grazed pasture on a drained peat soil. Glob Change Biol. 2005;11:607–618. doi:10.1111/j.1365-2486.2005.00929.x.
39. Robertson GP, Klingensmith KM, Klug MJ, et al. Soil resources, microbial activity, and primary production across an agricultural ecosystem. Ecol Appl. 1997;7:158–170. doi:10.2307/2269414.
40. Garten CT, Wullschleger SD. Soil carbon inventories under a bioenergy crop (switchgrass): measurement limitations. J Environ Qual. 1999;28:1359–1365. doi:10.2134/jeq1999.00472425002800040041x.
41. IPCC. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. 2006 IPCC guidelines for national greenhouse gas inventories. Volume 4: agriculture, forestry and other land use. Intergovernmental Panel on Climate Change. Prepared by the National Greenhouse Gas Inventories Programme. Hayama (Japan): IGES, 2006. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/.
42. Beniston JW, DuPont ST, Glover JD, et al. Soil organic carbon dynamics 75 years after land-use change in perennial grassland and annual wheat agricultural systems. Biogeochemistry. 2014;120:37–49. doi:10.1007/s10533-014-9980-3.
43. Collier SM, Ruark MD, Naber MR, et al. Apparent stability and subtle change in surface and subsurface soil carbon and nitrogen under a long-term fertilizer gradient. Soil Sci Soc Am J. 2017;81:310–321. doi:10.2136/sssaj2016.09.0299.
44. Kravchenko AN, Robertson GP. Whole-profile soil carbon stocks: the danger of assuming too much from analyses of too little. Soil Sci Soc Am J. 2011;75:235–240. doi:10.2136/sssaj2010.0076.
45. Ellert BH, Janzen HH, Entz T. Assessment of a method to measure temporal change in soil carbon

storage. Soil Sci Soc Am J. 2002;66:1687–1695. doi: 10.2136/sssaj2002.1687.
46. Conant RT, Smith GR, Paustian K. Spatial variability of soil carbon in forested and cultivated sites. J Environ Qual. 2003;32:278–286. doi:10.2134/jeq2003.2780.
47. Spencer S, Ogle SM, Breidt FJ, et al. Designing a national soil carbon monitoring network to support climate change policy: a case example for US agricultural lands. Greenhouse Gas Meas Manage. 2011; 1:167–178. doi:10.1080/20430779.2011.637696.
48. Lark RM. Estimating the regional mean status and change of soil properties: two distinct objectives for soil survey. Eur J Soil Sci. 2009;60:748–756. doi:10.1111/j.1365-2389.2009.01156.x.
49. Conant RT, Paustian K. Spatial variability of soil organic carbon in grasslands: implications for detecting change at different scales. Environ Pollut. 2002; 116:S127–S135. doi:10.1016/S0269-7491(01)00265-2.
50. de Gruijter JJ, McBratney AB, Minasny B, et al. Farm-scale soil carbon auditing. Geoderma. 2016;265: 120–130. doi:10.1016/j.geoderma.2015.11.010.
51. Bellon-Maurel V, McBratney A. Near-Infrared (NIR) and Mid-Infrared (MIR) spectroscopic techniques for assessing the amount of carbon stock in soils—critical review and research perspectives. Soil Biol Biochem. 2011;43:1398–1410. doi:10.1016/j.soilbio.2011.02.019.
52. Shepherd KD, Walsh MG. Review: infrared spectroscopy—enabling an evidence-based diagnostic surveillance approach to agricultural and environmental management in developing countries. J Near Infrared Spectrosc. 2007;15:1–20. doi:10.1255/jnirs.716.
53. Izaurralde RC, Rice CW, Wielopolski L, et al. Evaluation of three field-based methods for quantifying soil carbon. Plos One. 2013;8:e55560. doi:10.1371/journal.pone.0055560.
54. Viscarra Rossel RA, Behrens T, Ben-Dor E, et al. A global spectral library to characterize the world's soil. Earth Sci Rev. 2016;155:198–230. doi:10.1016/j.earscirev.2016.01.012.
55. Campbell EE, Paustian K. Current developments in soil organic matter modeling and the expansion of model applications: a review. Environ Res Lett. 2015; 10:123004. doi:10.1088/1748-9326/10/12/123004.
56. Paustian KO, Andren E, Davidson H, et al. Carbon dioxide from soils. Emissions and uptake of CO2 from soils. In: Revised 1996 IPCC guidelines for national greenhouse gas inventories:. Reference Manual. 1997.(Vol 3). Chapter 5. Land use change and forestry. 5.35-50. https:www.ipcc-nggip.iges.or.jp/public/gl/invs6.html [accessed June 29, 2019}
57. Ogle SM, Conant RT, Paustian K. Deriving grassland management factors for a carbon accounting method developed by the intergovernmental panel on climate change. Environ Manage. 2004;33: 474–484. doi:10.1007/s00267-003-9105-6.
58. Ogle SM, Breidt FJ, Paustian K. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry. 2005;72:87–121. doi:10.1007/s10533-004-0360-2.
59. Grant B, Smith WN, Desjardins R, et al. Estimated N 2 O and CO 2 emissions as influenced by agricultural practices in Canada. Climatic Change. 2004; 65: 315–332. doi:10.1023/B:CLIM.0000038226.60317.35
60. Wattenbach M, Sus O, Vuichard N, et al. The carbon balance of European croplands: A cross-site comparison of simulation models. Agriculture, Ecosystems & Environment. 2010;139:419–453. doi:10.1016/j.agee.2010.08.004
61. Jenkinson DS. The turnover of organic carbon and nitrogen in soil. Phil. Trans. Royal Soc. London B. 1990;329:361–368.
62. Falloon P, Smith P. Simulating SOC changes in long-term experiments with RothC and CENTURY: Model evaluation for a regional scale application. Soil Use and Management. 2002;18:101–111. doi:10.1079/SUM2001108.
63. Mccown RL, Hammer GL, Hargreaves J, et al. APSIM: An agricultural production system simulation model for operational research. Mathematics and Computers in Simulation. 1995;39:225–231. doi:10.1016/0378-4754(95)00063-2
64. O'Leary GJ, Liu DL, Ma Y, et al. Modelling soil organic carbon 1. Performance of APSIM crop and pasture modules against long-term experimental data. Geoderma. 2016;264:227–237. doi:10.1016/j.geoderma.2015.11.004
65. Moore AD, Eckard RJ, Thorburn PJ, et al. Mathematical modeling for improved greenhouse gas balances, agro-ecosystems, and policy development: lessons from the Australian experience. WIREs Clim Change. 2014;5:735–752. doi:10.1002/wcc.304
66. Del Grosso SJ, Parton WJ, Mosier AR, et al. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: M. Schaffer, L. Ma, L.S. Hansen (Eds.) Modeling Carbon and Nitrogen Dynamics for Soil Management. 2001. CRC Press, Boca Raton, Florida, pp 303–332
67. Nocentini A, Di Virgilio N, Monti A. Model simulation of cumulative carbon sequestration by switchgrass (Panicum virgatum L.) in the Mediterranean area using the DAYCENT model. Bioenerget Res. 2015;8: 1512–1522
68. Jones JW, Hoogenboom G, Porter CH, et al. The DSSAT cropping system model. European Journal of Agronomy. 2003;18:235–265. doi:10.1016/S1161-0301(02)00107-7
69. Gijsman AJ, Hoogenboom G, Parton WJ, et al. Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter–residue module from CENTURY. Agronomy J. 2002;94:462. doi:10.2134/agronj2002.4620
70. De Sanctis G, Roggero PP, Seddaiu G, et al. Long-term no tillage increased soil organic carbon content of rainfed cereal systems in a Mediterranean area. European Journal of Agronomy. 2012;40: 18–27. doi:10.1016/j.eja.2012.02.002
71. Yang M, Yang JY, Dou S, et al. Simulating the effect of long-term fertilization on maize yield and soil C/N dynamics in northeastern China using DSSAT and CENTURY-based soil model. Nutr Cycl Agroecosyst. 2013;95:287–303. doi:10.1007/s10705-013-9563-z.

72. Grant RF. Changes in soil organic matter under different tillage and rotation: Mathematical modeling in ecosystems. Soil Sci Soc Am J. 1997;61:1159–1175. doi:10.2136/sssaj1997.03615995006100040023x.
73. Grant RF, Juma NG, Robertson JA, et al. Long term changes in soil C under different fertilizer, manure and rotation: testing the mathematical model ecosys with data from the Breton Plots. Soil Sci. Soc. Am. J. 2001;65:205–214. doi:10.2136/sssaj2001.651205x.
74. Mekonnen ZA, Grant RF, Schwalm C. Sensitivity of modeled NEP to climate forcing and soil at site and regional scales: Implications for upscaling ecosystem models. Ecological Modelling. 2016;320:241–257. doi:10.1016/j.ecolmodel.2015.10.004
75. Lokupitiya E, Denning AS, Schaefer K, et al. Carbon and energy fluxes in cropland ecosystems: A model-data comparison. Biogeochemistry. 2016;129:53–76. doi:10.1007/s10533-016-0219-3
76. Apezteguia HP, Izaurralde RC, Sereno R. Simulation study of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Córdoba, Argentina. Soil Tillage Research. 2009;102: 101–108. doi:10.1016/j.still.2008.07.016
77. Zhang X, Izaurralde RC, Manowitz DH, et al. Regional scale cropland carbon budgets: Evaluating a geospatial agricultural modeling system using inventory data. Environmental Modelling & Software. 2015;63: 199–216. doi:10.1016/j.envsoft.2014.10.005
78. Grace PR, Ladd JN, Robertson GP, et al. SOCRATES—A simple model for predicting long-term changes in soil organic carbon in terrestrial ecosystems. Soil Biology and Biochemistry. 2006;38: 1172–1176. doi:10.1016/j.soilbio.2005.09.013
79. Grace PR, Colunga-Garcia M, Gage SH, et al. The potential impact of agricultural management and climate change on soil organic carbon of the North Central Region of the United States. Ecosystems. 2006;9:816–827. doi:10.1007/s10021-004-0096-9
80. AG-DEE. National inventory report 2015 Volume 2. Department of the Environment and Energy. 2017.
81. US EPA. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2017. Washington (DC): US Environmental Protection Agency; 2019. p. 675. (EPA 430-R-19-001).
82. Whittaker C, McManus MC, Smith P. A comparison of carbon accounting tools for arable crops in the United Kingdom. Environ Modell Softw. 2013;46: 228–239. doi:10.1016/j.envsoft.2013.03.015.
83. Paustian KM, Easter K, Brown A, et al. 2018. Field- and farm-scale assessment of soil greenhouse gas mitigation using COMET-farm. In: Delgado, JA, Sassenrath, Mueller, T. editors. Agronomy monograph: Precision conservation: geospatial techniques for agricultural and natural resources conservation. 59:361-384. Madison (WI): ASA and SSSA.
84. Wolfe ML, Richard TL. 21st century engineering for on-farm food–energy–water systems. Curr Opin Chem Eng. 2017;18:69–76. doi:10.1016/j.coche.2017.10.005.
85. van Wesemael B, Paustian K, Andrén O, et al. How can soil monitoring networks be used to improve predictions of organic carbon pool dynamics and CO2 fluxes in agricultural soils? Plant Soil. 2011;338: 247–259. doi:10.1007/s11104-010-0567-z.
86. Harden JW, Hugelius G, Ahlström A, et al. Networking our science to characterize the state, vulnerabilities, and management opportunities of soil organic matter. Glob Change Biol. 2018;24: e705–e718. doi:10.1111/gcb.13896.
87. Gaillard RK, Jones CD, Ingraham P, et al. Underestimation of N2O emissions in a comparison of the DayCent, DNDC, and EPIC Models. Ecol Appl. 2018;28:694–708. doi:10.1002/eap.1674.
88. Richards G, Evans D. Development of a carbon accounting model (FullCAM v1.0) for the Australian Continent. Austral For. 2004;67:277–283. doi:10.1080/00049158.2004.10674947.
89. Skjemsad JO, Spouncer L. Integrated soils modelling for the national carbon accounting system. Estimating changes in soil carbon resulting from changes in land use. Canberra: Australian Greenhouse Office; 2003. (36. National Carbon Accounting System Technical Report).
90. Alberta Agriculture and Forestry, Government of Alberta. Agricultural carbon offsets. Fact Sheet. n.d. [accessed 2017 Apr 20]. Available from: https://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/cl11618
91. McConkey BG, Haugen-Kozyra K, Staley D. Prairie soil carbon balance project summary: soil organic carbon change on direct-seeded farmland in Saskatchewan. University of Saskatchewan. 2013. Available from: http://www.usask.ca/soilsncrops/conference-proceedings/previous_years/Files/cc2000/docs/posters/018_post.PDF
92. Ellert BH, Janzen HH, McConkey BG. Measuring and comparing soil carbon storage. Boca Raton (FL): CRC Press LLC; 2001. p. 131–146.
93. Minasny B, Malone BP, McBratney AB, et al. Soil carbon 4 per mille. Geoderma. 2017;292:59–86. doi:10.1016/j.geoderma.2017.01.002.
94. Lefèvre C, Rekik F, Alcantara V, et al. 2017. Soil organic carbon: the hidden potential. Available from: https://www.cabdirect.org/cabdirect/abstract/20173155458.
95. Soussana J-F, Lutfalla S, Ehrhardt F, et al. Matching policy and science: rationale for the '4 per 1000–soils for food security and climate' initiative. Soil Tillage Res. 2017;188:3–15. doi:10.1016/j.still.2017.12.002.
96. Smith WN, Grant BB, Campbell CA, et al. Crop residue removal effects on soil carbon: measured and inter-model comparisons. Agric Ecosyst Environ. 2012;161:27–38. doi:10.1016/j.agee.2012.07.024.
97. Paul EA, Follett RF, Leavitt SW, et al. Radiocarbon dating for determination of soil organic matter pool sizes and dynamics. Soil Sci Soc Am J. 1997;61:1058–1067. doi:10.2136/sssaj1997.03615995006100040011x.
98. Basso B, Dumont B, Maestrini B, et al. Soil organic carbon and nitrogen feedbacks on crop yields under climate change. Agric Environ Lett. 2018;3: 180026. doi:10.2134/ael2018.05.0026.
99. Grunwald S, Thompson JA, Boettinger JL. Digital soil mapping and modeling at continental scales: finding solutions for global issues. Soil Sci Soc Am J. 2011;75:1201–1213. doi:10.2136/sssaj2011.0025.

100. Hengl T, de Jesus JM, MacMillan RA, et al. SoilGrids1km-global soil information based on automated mapping. PloS One. 2014;9:e105992. doi:10.1371/journal.pone.0105992.
101. Arrouays D, Bellamy PH, Paustian K. Soil inventory and monitoring: Current issues and gaps. Eur J Soil Sci. 2009;60:721–722. doi:10.1111/j.1365-2389.2009.01193.x.
102. Paustian K. Agriculture, farmers and GHG mitigation: a new social network? Carbon Manage. 2012;3:253–257. doi:10.4155/cmt.12.23.
103. Herrick JE, Urama KC, Karl JW, et al. The global Land-Potential Knowledge System (LandPKS): supporting evidence-based, site-specific land use and management through cloud computing, mobile applications, and crowdsourcing. J Soil Water Conserv. 2013;68:5A–12A. doi:10.2489/jswc.68.1.5A.
104. NRC. Verifying greenhouse gas emissions: methods to support international climate agreements. Washington (DC): National Research Council (NRC). National Academies Press; 2010. p. 110.
105. Hively W, Lamb B, Daughtry C, et al. Mapping crop residue and tillage intensity using WorldView-3 satellite shortwave infrared residue indices. Remote Sens. 2018;10:1657. doi:10.3390/rs10101657.
106. Bégué A, Arvor D, Bellon B, et al. Remote sensing and cropping practices: a review. Remote Sens. 2018;10:99. doi:10.3390/rs10010099.
107. Li C, Frolking S, Frolking TA. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. J Geophys Res. 1992;97:9759–9776. doi:10.1029/92JD00509.
108. Li C, Frolking S, Crocker GJ, et al. Simulating trends in soil organic carbon in long-term experiments using the DNDC model. Geoderma. 1997;81:45–60. doi:10.1016/S0016-7061(97)00080-3.
109. Smith P, Smith JU, Powlson DS, et al. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma. 1997;81:153–225. doi:10.1016/S0016-7061(97)00087-6.
110. Coleman K, Jenkinson DS, Crocker GJ, et al. Simulating trends in soil organic carbon in long-term experiments using ROTHC-26.3. Geoderma. 1997 ;81:29–44. doi:10.1016/S0016-7061(97)00079-7.
111. Cerri CEP, Easter M, Paustian K, et al. Simulating SOC changes in 11 land use change chronosequences from the Brazilian Amazon with RothC and Century models. Agric Ecosyst Environ. 2007;122:46–57. doi:10.1016/j.agee.2007.01.007.
112. Luo Z, Wang E, Sun OJ, et al. Modeling long-term soil carbon dynamics and sequestration potential in semi-arid agro-ecosystems. Agric For Meteorol. 2011;151:1529–1544. doi:10.1016/j.agrformet.2011.06.011.
113. Del Grosso SJ, Halvorson AD, Parton WJ. Testing DayCent model simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in Colorado. J Environ Qual. 2008;37:1383–1389. doi:10.2134/jeq2007.0292.
114. Del Grosso SJ, Gollany HT, Reyes-Fox M. Simulating soil organic carbon stock changes in agroecosystems using CQESTR, DayCent, and IPCC Tier 1 methods. In: Del Grosso SJ, Ahuja LR, Parton WJ, editors. Synthesis and modeling of greenhouse gas emissions and carbon storage in agricultural and forest systems to guide mitigation and adaptation. 2016. Adv Agric Syst Model. Vol 6, p. 89–110. ASA, CSSA and SSSA, Madison, WI. doi:10.2134/advagricsystmodel6.2013.0001.5.
115. Izaurralde RC, Williams JR, McGill WB, et al. Simulating soil C dynamics with EPIC: model description and testing against long-term data. Ecol. Modell. 2006;192:362–384. doi:10.1016/j.ecolmodel.2005.07.010.
116. Izaurralde RC, Haugen-Kozyra KH, Jans DC, et al. Soil organic carbon dynamics: measurement, simulation and site to region scale-up. In Lal R, Kimble JM, Follett RF, Stewart BA, editors. Assessment methods for soil carbon. Boca Raton (FL): Lewis Publishers; 2001, p. 553–575.
117. Australian Government Department of the Environment and Energy. http://www.environment.gov.au/.